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Analysis of Space Tug Operating Techniques
Final Report (Study 2.4)
Volume II: Study Results

Prepared by
ADVANCED VEHICLE SYSTEMS DIRECTORATE

August 1972

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

Contract No. NASw-2301

Systems Engineering Operations
THE AEROSPACE CORPORATION

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FOREWORD

Study 2.4, "Analysis of Space Tug Operating Techniques," was managed by the Advanced Missions Office of the NASA Office of Manned Space Flight. Dr. J. W. Wild was the Technical Director of this study; day-to-day management was performed by Mr. R. R. Carley. Mr. R. E. Kendall was The Aerospace Corporation Study Director from study initiation until 3 April 1972. Dr. L. R. Sitney directed the Study from that date through completion.

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I. INTRODUCTION

This report summarizes the major portion of the work done on Study 2.4, "Analysis of Space Tug Operating Techniques," of Contract NASw-2301. Other tasks performed under Study 2.4 are reported in Study 2.3 final report and a supplemental report on Study 2.4. These other tasks are defined later in this section. The following tasks were considered as potential specific study tasks for Study 2.4.

Task 1 - Impact of DOD-Unique Requirements on an ELDO-Designed Tug

Task 2 - Utility of a Non-Autonomous DOD Tug

Task 3 - Licensing Considerations (Of an ELDO Tug)

Task 4 - Identification of Tug Subsystem Cost Drivers

Task 5 - Conceptual Design and Operation of a Payload Retrieval Mechanism

Task 6 - Conversion of MSFC Tug Point Design to NASA/DOD Multi-Purpose Tug Design

Task 7 - Tug Technology Requirements

Task 8 - ELDO Technology Assessment

Task 9 - Tug Refurbishment Costs

Tasks 1 and 9 were selected for first priority, the former being limited to a review of available documentation from the ELDO Phase A Studies, the ELDO Phase A Statement of Work and DOD OOS Studies. Participation in the ELDO Tug Subsystem Design Reviews anticipated for July 1972 was planned by Aerospace as part of Task 1. This effort was not expended due to cancellation of the ELDO Subsystem Review Meetings as a result of the termination of the ELDO Tug activities. A preliminary one-month assessment of Tug refurbishment costs was made on Task 9 utilizing existing cost estimating relationships (CERs). The results were of sufficient

interest to warrant an in-depth "bottoms-up" analysis of Tug refurbishment costs. A detailed study plan was then submitted to the NASA Technical Director and, following its approval, the "bottoms-up" analysis was initiated. This analysis used the total remaining study manpower.

During May 1972 a NASA review of the refurbishment effort (Task 9) resulted in the following recommendations for the remaining refurbishment effort.

Item 1 - Improve Refurbishment Estimates and Review Design Impacts

a. Define Tug fault detection methods for each Tug major system.

b. Identify test points and sensors for fault isolation of each system listed above.

c. Continue review of refurbishment man-hour estimates to assure common base for estimates and to describe unusual man-hour requirements.

d. Review tank insulation refurbishment approach.

e. Review auxiliary propulsion system refurbishment approach for possible reduction in man-hour requirements.

f. Investigate new tank design approach.

g. Clarify fuel cell refurbishment estimate.

h. Summarize the refurbishment vehicle design impacts (requirements) as determined from the refurbishment studies.

Item 2 - Establish Study Parameters to Determine Impact on Refurbishment of NASA/USAF Two Launch Site Concept.

Item 3 - Refurbishment Engineering Support Requirements

a. On-site vehicle and subsystems.

b. Off-site vehicle and subsystems.

With the exception of Items 1a, 1b, and 3, these items were accomplished by the end of the study. Items 1a, 1b, and 3 were addressed at the end of the study period in a very broad sense, however, and are reported separately in Aerospace report ATR-73(7314)-2. Item 2 was not addressed to any depth due to the low (less than four flights per year) anticipated Tug traffic rate from the Western Test Range (WTR).

During the FY 1972 effort, the following Tug activities were supported jointly by Studies 2.3 and 2.4:

1. Tug Implications of Mark I/Mark II Shuttle Program
2. ELDO Phase B Cost Estimates

and are reported as part of Study 2.3, Aerospace report ATR-73(7313-01)-1.

This document therefore contains only the effort expended on Task 9, Tug Refurbishment Costs. The objectives of this effort were to determine the average cost of maintaining the Tug after each mission, identify design requirements of selected systems and identify areas that required subsequent study.

The task of determining the cost of maintaining and refurbishing a vehicle before that vehicle has ever been used is a difficult job. The problem of determining these costs for a vehicle, such as the Tug, that is still in the conceptual phase is even a more formidable one. Without any detailed information regarding the design of the various subsystems, any estimate of the refurbishment costs would be mainly conjecture. To help circumvent this problem, a baseline vehicle was synthesized from data obtained from NASA and DOD funded Tug/OOS studies and Aerospace in-house efforts. Each major vehicle system was described and the operations necessary for

maintenance of each one of the systems were defined. The impact of multiple reuse on the design and operation of spacecraft systems is not well understood. In lieu of an existing data source directly applicable to Tug refurbishment, the experience that has been gained on past and current Air Force space programs was utilized as the main source of information for this study. Many of the systems and subsystems used on these programs, even though they were not designed for reuse, are similar to those that are currently planned for Tug use. Various vendors and manufacturers whose ideas were solicited in regard to the effect of multiple reuse and the cost of refurbishment on their particular equipment were another important source of data. Engineering judgment was used to synthesize these data into a viable approach to Tug refurbishment.

The methods and philosophies used in the maintenance and refurbishment of current reusable vehicles such as commercial and military aircraft are a data base which could be utilized to establish some ideas for the approach to Tug maintenance. However, the differences between these types of vehicles and the Tug in their design and operating modes may not permit a valid comparison of maintenance costs. No attempt was made to compare the study results with the costs associated with maintaining and refurbishing current reusable vehicles.

Vehicle maintenance cost is proportional to the time and effort expended in checkout and testing of the vehicle systems during the post-flight maintenance cycle. Definition of the test points and system self-check capability is a prerequisite for determining the actual effort required to ascertain system status; however, the state of the design of the Tug systems, e.g., the checkout and fault isolation system, does not permit a detailed assessment of the test points and self-check requirements. Hence, some gross assumptions were necessarily made relative to the determination of vehicle status. It was assumed for this study that an on-board checkout and switching system could be developed that could detect all important failures and switch in the redundant component or subsystem. The failure rate of the built-in test

equipment (BITE) was assumed to be 10 percent of the total system. The relative complexity of the BITE system and the system being tested was not assessed. No determination of the failure detection probability was made; however, 25 percent was added to all costs associated with random failures to account for false alarms. The redundancy and reliability requirements of the redundancy switching system were not addressed. The results of this study are predicated on the existence of such equipment for redundancy switching and minimizing the amount of ground checkout required between flights. A separate study is needed to define the system that accomplishes this function.

II. SUMMARY

A. VEHICLE DESCRIPTION

The vehicle used for this study was synthesized from data obtained from NASA and DOD funded Tug/OOS studies and Aerospace in-house efforts. The vehicle is an integral propulsion stage utilizing liquid hydrogen and liquid oxygen as propellants and is capable of operating either as a fully or a partially autonomous vehicle. Structural features are an integral LH_2 tank (mounted forward), an LO_2 tank (mounted aft), a meteoroid shield, an aft-conical docking and structural support ring and a new staged combustion main engine. The vehicle is constructed of major modules for ease of maintenance.

B. REFURBISHMENT COST ESTIMATE

The baseline vehicle was divided into eleven major vehicle areas for which refurbishment costs were generated. Table II-1 shows the average refurbishment cost per mission for each of these areas. Phase II and Phase III in Table II-1 refer to different phases of the flight program. Phase II refers to the initial operational capability (IOC) portion of the flight program which consists of the first 20 flights after the flight test program. Phase III is the operational capability (OC) portion of the flight program and the refurbishment costs associated with this phase are for a mature vehicle. Scheduled refurbishment costs refer to the costs associated with planned maintenance and replacement. Unscheduled refurbishment costs refer to costs associated with random failures.

The average refurbishment cost for an initial operational vehicle (IOC) is \$429,000 per flight as compared to \$273,000 per flight for a mature vehicle (OC). The reduction in the average maintenance cost is due to a reduction in the scheduled hardware replacements and detailed inspections that are performed during IOC. The purpose of these detailed inspections is to aid in developing and determining the reusability of the various systems. In addition, the unscheduled maintenance costs in the OC phase

Table II-1. Tug Refurbishment Cost Per Mission - Thousands of Dollars

	PHASE II - IOC			PHASE III - OC		
	Scheduled	Unscheduled	Total	Scheduled	Unscheduled	Total
Basic Structure	0.6	0	0.6	0.6	0	0.6
Meteoroid Shield	11.0	0	11.0	11.0	0	11.0
Tug-P/L Dock.	5.4	1.3	6.7	5.4	0.6	6.0
Tug-Shuttle Dock.	2.9	0.3	3.2	2.9	0.1	3.0
Propel. Tanks	15.5	28.5	44.0	15.5	14.3	29.8
Interface Panels	11.3	0.2	11.5	10.3	0.1	10.4
Tank Insulation	64.6	3.6	68.2	48.3	1.8	50.1
Main Prop.	36.5	34.5	71.0	19.8	17.3	37.1
Aux. Prop.	85.6	35.0	120.6	44.9	17.5	62.4
Elect. Power	30.2	4.5	34.7	27.3	2.2	29.5
Avionics	4.4	34.2	38.6	2.9	17.1	20.0
System Tests	18.7	0	18.7	12.7	0	12.7
TOTAL	286.7	142.1	428.8	201.6	71.0	272.6

represent a mature system whereas in the IOC phase of the program the mean time between failure (MTBF) of the various systems is assumed to be only half of its mature value for each system.

The scheduled maintenance costs represent the major portion of the total refurbishment costs except for the avionics system, where the unscheduled maintenance costs for the avionics systems are approximately 6 times higher than the scheduled maintenance for a mature vehicle. This is due to the maintenance philosophy assumed for the avionics system in which nothing is replaced unless it fails. This philosophy is possible because the system contains significant redundancies and essentially never wears out. This type of philosophy is not feasible for a system like the propellant tank insulation system or the main propulsion system where there are definite wear-out modes and the systems are not redundant.

Table II-2 presents the refurbishment costs for IOC and OC as a percentage of the vehicle first unit production cost. The cost for IOC is 3.91 percent and 2.49 percent for OC. These percentages are made up of five main drivers. For OC, these are in order of importance: (1) the auxiliary propulsion system, (2) the propellant tank insulation system, (3) the main propulsion system, (4) the propellant tanks, and (5) the electrical power system. In the IOC phase, the avionics system is more expensive to maintain than the electrical power system. This is a result of the relative immaturity of the system in the IOC phase of the program and the fact that almost all the cost of maintaining the avionics system is due to unscheduled maintenance. The major cost of maintaining the electrical power system is for scheduled maintenance which is about the same for both flight phases.

Table II-2. Tug Refurbishment Costs - Percent Per Flight *

	IOC	OC
Basic Structure	0.01	0.01
Meteoroid Shield	0.10	0.10
Tug-P/L Dock.	0.06	0.05
Tug-Shuttle Dock.	0.03	0.03
Propel. Tanks	0.40	0.27
Interface Panels	0.10	0.09
Tank Insulation	0.62	0.46
Main Prop.	0.65	0.34
Aux. Prop.	1.10	0.57
Elect. Power	0.32	0.27
Avionics	0.35	0.18
System Tests	0.17	0.12
TOTAL	3.91	2.49

* Percent of vehicle first unit production cost per flight.

First Unit Hardware Cost

	$ Millions
Structure	2.02
Avionics	3.53
Elect. Power	1.07
Propulsion	3.39
Integration, Assembly, Checkout and Test	0.96
	10.97

III. CONCLUSIONS AND RECOMMENDATIONS

A. DESIGN REQUIREMENTS OF SELECTED TUG SYSTEMS

The results of this study are strongly dependent on the capability of the Tug vehicle to be easily maintained and refurbished. Various assumptions made during the course of the study can be related to design requirements for many of the major vehicle areas. The first and most significant assumption made in this study was that the vehicle was designed to be maintained and refurbished. If the costs of maintaining a reusable vehicle like the Tug are to to be similar to the estimates made in this study, a design requirement of maintainability and refurbishability must be imposed. This requirement must be imposed at the very beginning of the design phase rather than at some later date in the design as an afterthought. The vehicle must be designed in such a way as to allow components that have limited life and high maintenance requirements to be easily removed and replaced. This must be done with a minimum amount of impact on the remainder of the vehicle.

The results of this study point out the areas which have the greatest effect on the cost of Tug refurbishment. The depth of this study does not permit the identification of specific design requirements; however, this study does identify general requirements that either are necessary if one is to achieve the estimated refurbishment cost estimate or can be a significant factor in reducing the refurbishment cost of the vehicle. The following paragraphs address the five major cost drivers identified for the mature vehicle and attempt to establish some general requirements relative to these systems.

Auxiliary Propulsion System

The auxiliary propulsion system has been identified as the most costly Tug system to maintain. This is due primarily to the complexity and initial cost of the system. The system has certain wearout modes which necessitate the scheduling of replacement maintenance cycles. The ratio of manpower costs to hardware costs for maintaining the system is approximately

13 percent. Therefore, any significant reduction in the cost of maintaining the system must be accomplished via the hardware route. The auxiliary propulsion system is assumed to have a life of 20 missions before major overhaul. After 20 missions, the system is refurbished at a cost of 33 percent of the cost of a new system. The maintenance cost of the system could be reduced by designing for a longer life, designing to a lower refurbishment cost factor, or both. A design life of 20 missions was assumed for this study. The 20 mission life capability of the main engine was used as a guide for this assumption. The 33 percent refurbishment cost factor used for the auxiliary propulsion system was determined by looking at the operations involved and the disposition of the various components removed during the refurbishment of the system.

Two design requirements are apparent for the auxiliary propulsion system as a result of refurbishability and maintainability: (1) the system must have a design life of 20 missions between major overhauls with a design goal of 40 missions, and (2) at the end of the design life the system must be refurbishable at a cost not to exceed 25 percent of the cost of a new unit with a design goal of 15 percent.

Propellant Tank Insulation System

The second most costly item to maintain is the tank insulation system. This is due to the state of development of the system. Currently, the reusability of the system has strong limitations and hence costly replacement and repair maintenance cycles are scheduled. The cost of the maintenance of this system is relatable to the design life of the system. The design requirement for the propellant tank insulation system should be that the system will have a minimum design life of 20 missions before major overhaul with a design goal of 100 missions.

Main Propulsion System

One of the requirements that has been defined for the main engine by the Air Force Rocket Propulsion Laboratory (AFRPL) is that it will have a

10 hour operational life before major overhaul. For the particular missions defined for the Tug, this is equivalent to 20 missions. Also, analytical studies that have been performed by the various engine contractors have indicated that the engine can be refurbished after 10 hours of operation for 25 percent of the cost of a new unit.

This refurbishment study has assumed that the main engine has a 20 mission capability after which it can be refurbished for 25 percent of the cost of a new unit. The capability of a maximum refurbishment cost after 10 hours operation of 25 percent of the cost of a new engine should be made a firm requirement.

Propellant Tanks

The propellant tank life for this study was assumed to be 20 missions after which the tanks were replaced. This assumption results in two design requirements: (1) the tank must be designed for a minimum of 20 mission life with a design goal of 100; and (2) the vehicle must be designed for tank replacement.

Electrical Power

The electrical power system was assumed to have a design life of 2000 hours after which it could be refurbished for 25 percent of the cost of a new unit. The 2000 hour design life is a requirement for a currently funded fuel cell technology study. The refurbishment cost factor of 25 percent is not. The design requirement for the electrical power system resulting from the refurbishment study is that the system have the capability of being refurbished at a minimum cost of 25 percent of a new unit after 2000 hours of operation. The design goal for refurbishment should be 15 percent.

B. TECHNOLOGY REQUIREMENTS

Several technology requirements have become apparent during the course of the refurbishment study. The first of these pertains to the propellant tank insulation system. The multilayer insulation system is one of the main

refurbishment cost drivers mainly because of the unknowns involved with its reuse capability. The current estimate of its reuse capability is that it must be replaced every 5 missions due to deterioration under repeated exposure to the ascent and reentry environment. The technology requirement is to develop more test data on the insulation to gain a better understanding of the effect of repeated exposure to the ascent and reentry environment. This understanding should result in the development of an insulation system that has a life expectancy of 20 missions or more.

The problem of testing the insulation system after each mission has resulted in another technology requirement for the tank insulation system. Multilayer insulation (MLI) must be located in a vacuum environment to perform properly. Generally, space provides the necessary vacuum to permit MLI to perform thermally as it is intended to perform. At sea level conditions, space-evacuated MLI will be filled with air or with a non-condensable gas as a result of purging. In such a condition, the thermal protection afforded by the insulation will be radically reduced. Because of the difference in MLI thermal performance at sea level and high vacuum conditions, there presently is no method to verify MLI space performance without subjecting it to a vacuum test. A method to circumvent this problem is needed. The effort should be directed toward detecting the most common failure modes of the insulation. These are insulation crushing, insulation delamination, joint thermal shorts, etc. Techniques such as X-ray examination may be promising. If testing under ambient ground conditions turns out to be an infeasible method, testing at a moderate vacuum should be investigated.

Several technology requirements have been identified for the successful implementation of large, thin walled propellant tanks for the Tug vehicle. The technology requirements encompass cyclic life considerations, methods of leak checking, and fracture mechanics data characterization.

On the basis of demonstrated cyclic lives of a few hundred cycles for current aerospace thin-walled tanks such as the Titan IIIC Transtage and the Atlas/Centaur, it was concluded that the Tug 20 mission requirement could be

met with test and quality control standards similar to procedures used on those programs. Since the Tug tankage is a different material than the materials used in those programs, i.e., aluminum versus titanium (Titan IIIC Transtage) and stainless steel (Atlas/Centaur), a technology requirement is identified consisting of subscale, or full scale Tug tankage subjected to cyclic pressure loading and monitored for leakage. The consideration of tank life extension from 20 missions to 100 missions (200-1000 pressure cycles) also identifies a technology requirement for cyclic pressure testing.

For the routine maintenance of the propellant tanks, a tank leak test with helium was proposed. Although equipment is currently available for such a test, it is necessary to establish a technology requirement to develop small portable devices which could be used conveniently for tank checkout between missions. In addition, the problems associated with detecting helium leakage from tankage covered with thermal insulation should be investigated.

Pressure vessels often contain small flaws, or defects, that are inherent in the materials, or introduced during the fabrication process. These flaws may, in some cases, reduce the load-carrying capability and operational life of the component from the levels predicted by conventional methods of analysis. Fracture mechanics provides a methodology for evaluating the influence of flaws on pressure vessel performance and failure mode. The application of this design method to the Tug tankage is severely hampered by the lack of data for flaws in thin-walled tanks. Therefore, a technology requirement is established for empirical data on pressure vessels with part-through thickness flaws subjected to cyclic pressure. The test program should investigate the cycles to leakage of thin-walled propellant tanks representative of the Tug vehicle due to initial part-through cracks. The program should investigate several aluminum alloys appropriate for cryogenic tankage, several parameters involving flaw geometry (i.e., depth-to-length ratios) and flaw depth-to-tank wall thickness, the influence of temperature, and the influence of tank wall stress levels.

C. RECOMMENDED ADDITIONAL STUDY AREAS

Vehicle Study

The Tug is basically a high performance vehicle that is very sensitive to weight. Historically, vehicles designed for space application have been designed for minimum weight and volume. This has resulted in the development of highly complex mechanical and electrical packaging techniques. For a reusable vehicle, such as the Tug, that must be maintained and refurbished many times, this type of design philosophy is not appropriate. A new design philosophy must be used which stresses ease of maintenance and accessibility to various systems. A vehicle study should be performed to assess the feasibility of such a design philosophy. The vehicle would be designed with the requirement that it be maintainable and refurbishable. Trade studies should be performed to determine the effect on total program cost of varying RDT&E costs and the resultant changes in maintenance and refurbishment costs. The average cost per mission of maintaining this vehicle would then be determined and its performance compared with a Tug that has been designed for maximum performance without regard to maintenance.

Checkout and Fault Isolation System Definition

The time consumed and the manpower involved in determining the status of each system before and after each flight is dependent on the amount of ground checkout required. The results of this study are based on the existence of an on-board checkout and switching system that could detect all important failures and switch in the redundant component or subsystem. A study is needed to define the onboard checkout and fault isolation system (COFI). The study should determine the best mix of on-board and ground COFI and operational flight support. Several approaches and their impact on the total vehicle should be examined. The failure rate of the built-in test equipment and the redundancy and reliability requirements of the redundancy switching system should be determined.

Total Tug Turnaround Costs

The study reported herein is concerned with only one part of the total Tug turnaround costs, viz., maintenance and refurbishment. Currently, Tug turnaround costs are estimated using cost estimating relationships (CER s) based on experience gained from past programs. A study is needed to develop comprehensive estimates of the costs associated with Tug turnaround from launch to launch based on an assessment of the operations involved as they specifically apply to the Tug. All cost estimates should be developed by assessing the functions, manpower and hardware necessary to support each of the Tug turnaround operations.

Tug Refurbishment Logistics Concepts

A study is needed to assess the various approaches to Tug logistics. Various concepts concerning the approach to vehicle maintenance should be identified. The question of who will perform the maintenance and the impact on the total program should be addressed, e.g., private contractor versus the use of a government organization to perform vehicle maintenance. The impact on the funding level and the level of support required at the manufacturer for various approaches to spares support should be identified, e.g., all spares purchased at the beginning of the program or purchased over a longer time span.

IV. DISCUSSION

The purpose of this study was to establish, by a "bottoms-up" analysis, the cost of maintaining the reusable third stage of the Space Transportation System, viz., the Tug. Design effects and requirements of selected components that result from the refurbishment function were to be identified. Also, areas requiring in-depth subsequent studies were to be identified.

A. APPROACH

A list of ground rules and assumptions were generated on which the study was based. These covered basic design philosophy required for a refurbishable vehicle, assumptions concerning fault isolation and replacement of failed components, and the portion of Tug ground operations considered as Tug refurbishment.

A baseline vehicle was synthesized from available data obtained from both funded and in-house Tug/OOS studies. The vehicle was divided into eleven major vehicle areas:

1. Basic Structure
2. Meteoroid Shield
3. Tug/Payload Docking Mechanism
4. Tug/Shuttle Docking Mechanism
5. Interface Panels
6. Propellant Tanks
7. Propellant Tanks Insulation System
8. Main Propulsion System
9. Auxiliary Propulsion System
10. Electrical Power
11. Avionics

Basic data was then generated for each of the eleven major vehicle areas. This was done by means of "Refurbishment Data Sheets" and "Refurbishment Operations Sheets." The "data sheets" contain all of the pertinent descriptive information for each of the major vehicle areas, viz., the function of the equipment, physical characteristics such as weight and size, an estimate of the unit cost and maturity of the equipment, expected failure modes and rates where known and an estimate of the cost to refurbish the piece of equipment. The "operations sheets" describe the actual tasks that are necessary to keep the equipment functioning properly, the frequency at which the tasks are performed, the hardware replaced during the tasks and an estimate of the manpower required to perform the tasks. The refurbishment data sheets and operations sheets for each of the eleven major vehicle areas are contained in Appendix I.

From the data and operations sheets, an estimate was made of the scheduled maintenance costs for each subsystem. Next, using the information available on subsystem mean time between failure, an estimate was made of the subsystem maintenance costs due to random failures. The total Tug refurbishment costs were then tabulated and the cost drivers identified. Refurbishment design effects and requirements of selected Tug systems that have a significant effect on refurbishment costs were identified. An assessment was also made of areas that are of major concern to refurbishment and which require subsequent in-depth studies.

The data used in this study came from many sources. Tug/OOS vehicle contractors were surveyed for applicable information. The NASA Tug and Air Force OOS funded studies were utilized where appropriate. Various component vendors were canvassed relative to their particular hardware. In-house specialists who have experience in past and current Air Force space programs in each of the major vehicle areas were utilized. From these sources a data base was established from which a best estimate of the cost to maintain the Tug was made.

B. GROUND RULES AND ASSUMPTIONS

The first and most important assumption made in this study is that the vehicle must be designed for ease of maintenance. All of the manpower estimates are based on the assumption that components can be easily removed and replaced in the vehicle. In addition, the vehicle should be built up of major subsystem modules so that the vehicle can be readily disassembled into its major subsystems as depicted in Figure IV-1.

For the purpose of this study, it was assumed that all Tugs are successfully launched by the Shuttle, complete their mission, and are successfully returned to the launch site by the Shuttle. In-flight Tug failures are detected on board and the redundant component is used to successfully complete the mission.

The Tug system includes built-in test equipment (BITE) to the component level. Wiring and connector reliabilities are assumed to be part of the component reliability.

The baseline vehicle is composed of components/assemblies such as star trackers, computers, etc. These items are, by definition, the Line Replaceable Units (LRU) and, if they fail in flight, the Checkout and Fault Isolation (COFI) system, in conjunction with the Tug data management and software systems, automatically switch in the redundant component/assembly. When the Tug returns to the maintenance area, the failed or indicated failed component/assembly is found by inspection, post-flight tests, flight recorder data, etc., removed, replaced, checked out with regard to its own system/subsystem and then verified by a post-maintenance vehicle level test. The failed component is taken to the repair depot for refurbishment and then returned to the maintenance storeroom. The repair depot may be at the maintenance area or located off-site. For the purposes of this study, it has been assumed that this repair is costed out at a certain percentage of the unit cost, ranging from 15 percent to 60 percent depending on the item. The actual manpower identified with this effort is only that necessary for removal

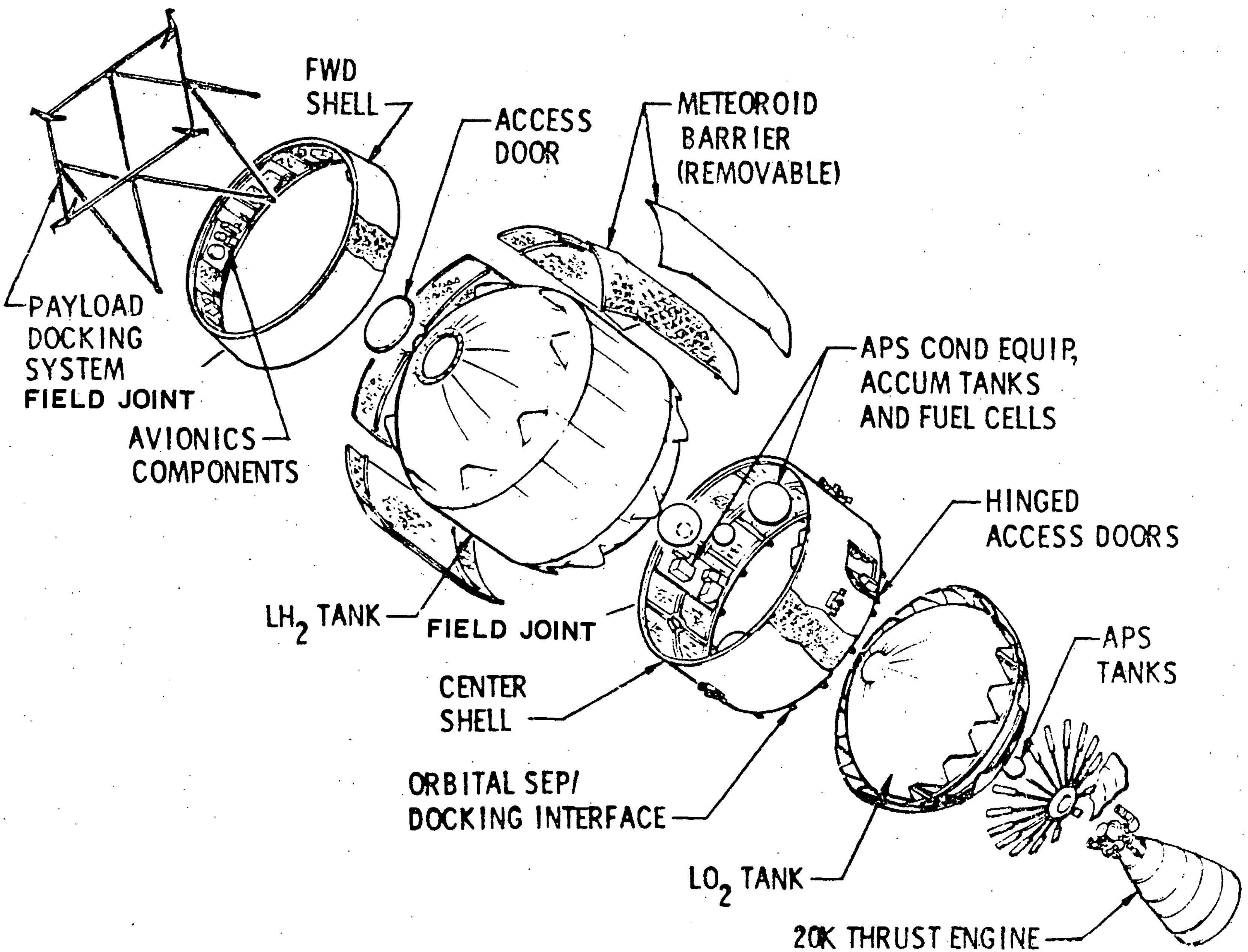

Figure IV-1. Design for Access and Maintenance

and replacement of the component on the vehicle. Therefore, whether or not this repair is performed on or off-site is immaterial as far as this study is concerned. The actual tradeoffs to determine whether this repair is done off-site or on-site should be the subject of a subsequent study.

The previous paragraph implies the assumptions that all indicated failures result in component replacement prior to the next mission and that the maintenance costs and rates reflect both real failures and false alarms.

Another important assumption concerns the portion of the actual ground turnaround operations considered to be part of Tug maintenance. Figure IV-2 is a block diagram depicting the ground turnaround operations. The only portion of the turnaround cycle considered in this study is that portion which occurs after the Tug has been safed and unloaded from the Shuttle and before the Tug is turned over for prelaunch operations as a "new" vehicle. The operations considered for this study are those involved with transporting the Tug to the maintenance area, analyzing the flight data, performing the pre-maintenance vehicle level test, performing the actual maintenance operations and then performing the post-maintenance vehicle level test. At this point, the vehicle is considered to be as a "new" vehicle and the subsequent operations are charged to other functions. The vehicle at this time may be put in storage for later use or sent on to the pre-launch activity area.

The cost of ground equipment is not considered in this study, only the manpower required to operate it. Some of the special ground equipment required as a result of Tug maintenance is identified but not costed.

C. BASELINE VEHICLE

This section of the report describes the vehicle used during the study. The eleven major vehicle areas are described to the depth necessary to provide an understanding of the operations involved in maintaining and refurbishing the vehicle. The vehicle used for this study was synthesized from data obtained from DOD-funded OOS studies and Aerospace in-house efforts. Results of the NASA Tug Point Design studies were also utilized.

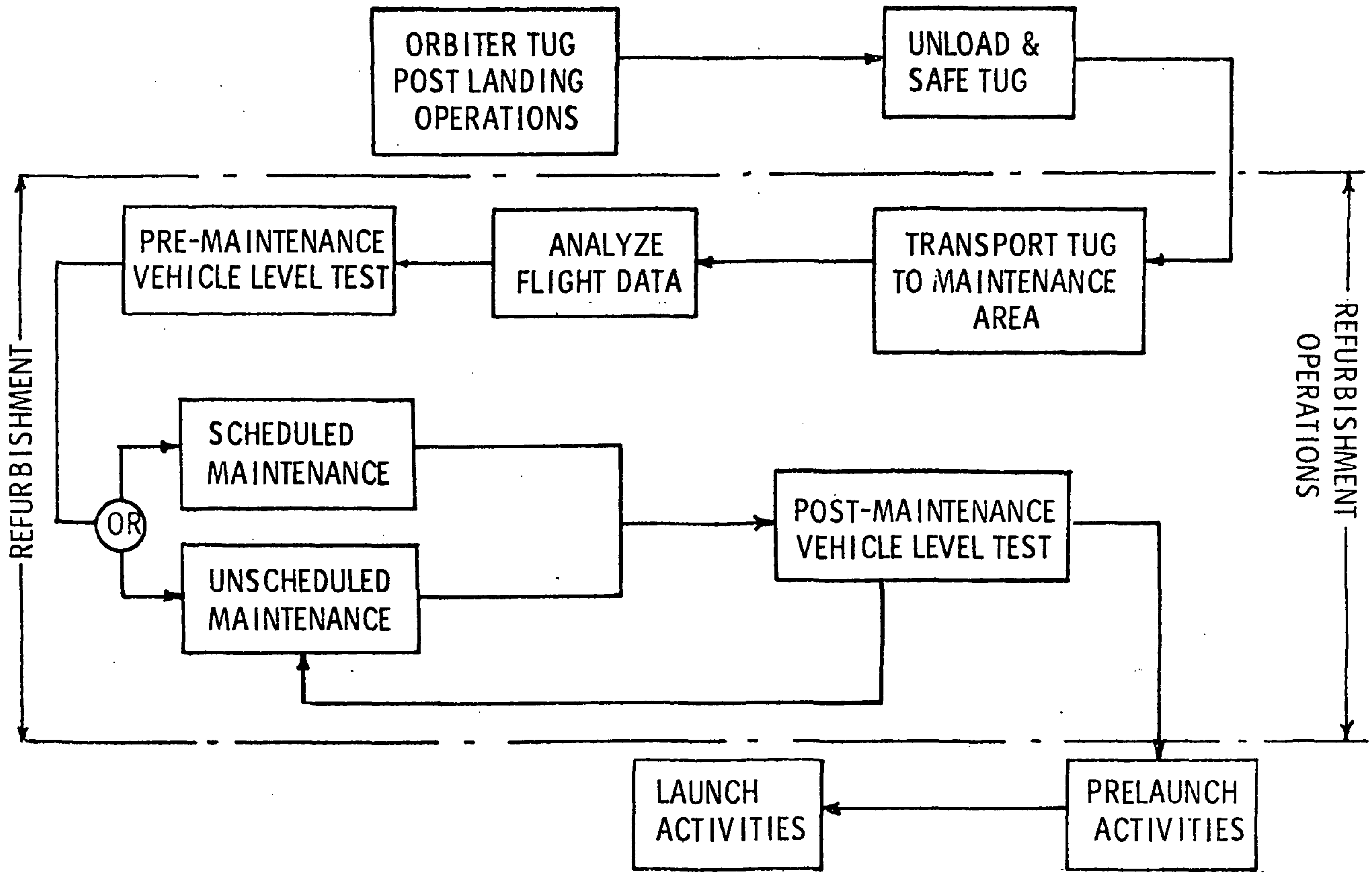

Figure IV-2. Tug Refurbishment/Maintenance Operations

The Tug/OOS is a high performance upper stage vehicle designed to operate as a ground-based vehicle. The Tug/OOS is an integral propulsion stage utilizing liquid hydrogen and liquid oxygen as propellants and is capable of operating either as a fully or a partially autonomous vehicle. Structural features are an integral LH_2 tank (mounted forward), an LO_2 tank (mounted aft), a meteoroid shield, an aft-conical docking and structural support ring and a new staged combustion main engine. The Avionics subsystems such as navigation, guidance and control, data management, and part of the communications, are located between the payload interface bulkhead and the liquid hydrogen tank. The reaction control equipment, electrical power equipment, radiator and part of the communications equipment are located in the annular compartment between the liquid propellant tanks. The reaction control thrusters are located on the outside of this compartment. The primary Shuttle adapter structural attachments are made at the heavy ring frame at the aft end of this compartment while the forward attachment is made at the forward bulkhead which also serves as the payload interstage mounting plane. For ease of maintenance, the vehicle is constructed of major module assemblies as shown in Figure IV-1.

Basic Structure

The baseline vehicle utilizes separate tanks with elliptical domes, integrated structure/LH_2 tank and a single staged combustion engine. Materials utilized in fabrication are 2219-T87 aluminum alloy for tankage, aluminum alloy thrust structure and interface rings, and Boron filament reinforced epoxy skin-stringer shell skirts and intertank structure. Boron epoxy is used as tank skirt and intertank structure to serve as a thermal bridge and minimize heat leaks. Structural supporting ties to both ends of the load-carrying LH_2 tank are non-metallic, tubular truss members at 12 discrete points to reduce penetrations of the tank insulation. The tubes are filament wound fiberglass with integral titanium fittings at each end, hinged to permit the tank to breathe radially under cryogenic shrinkage and pressure extension. The hinge points also provide for ready assembly/disassembly

of stage structural elements. Thrust loads are concentrated in tubular trusses which dump into the same hard points as the aft LH_2 tank truss members. At the forward end of the LH_2 tank, truss members extend forward to the aft end of the avionics unit. Straight columns, stabilized by shear panels, carry the loads across this unit and into the basic stage structural support ring at the forward end of the unit from which they are dumped into the support cradle and the Shuttle. Trussed supports from the LO_2 tank and payload react their loads into the same hard points and into the Tug frame and cradle. The hard interface points between the Tug and the Shuttle, while the Tug is housed in the orbiter payload bay, are the deployment/retrieval mechanism, the structural attachment and support points, and the electrical and fluid interface connections.

Meteoroid Shield

The various theories associated with meteoroid flux, mass, density, sporadic shower phenomena, velocity, and penetration characteristics can be analyzed in such a manner that there can be an order of magnitude difference in the meteoroid shield requirements. In addition, the degree of protection desired, the element of acceptable risk, and the probability additive factor of multiple reuse are three more variables that heavily influence the results of a meteoroid analysis. However, the results of this study are not affected by the actual detailed design of the shield. For this study, the meteoroid shield is assumed to be a double-walled aluminum shield consisting of 1.3×10^{-2} cm (0.005 in) face sheets spaced 2.54 cm (1.0 in) apart. The filler material between the sheets consists of an open cell foam material.

Tug/Payload Docking Mechanism

The mechanical attachment between the payload and the Tug is accomplished through a mechanism attached to the Tug forward mounting plane. One possible mechanism consists of four guide arms and capture latches which are connected by straight sections of aluminum tubing. Each guide

arm is joined to the stage skirt by a pair of shock absorber/actuators. The guide arms and capture latches are coated with fiberglass-reinforced teflon.

The forward frame provides for the support of a payload attached to the Tug through 24 electrically actuated latches. Acquisition and docking with the payload are accomplished with a square-frame type docking system incorporating an attenuated square frame and capture latches on the Tug vehicle which is engaged by guides on the payload. The square frame attenuators are attached to the 30.5 cm (12 in) deep frame aft of the separation plane. Once the payload has been captured, it is pulled down by the pneumatic system and the final hard latching is accomplished by the 24 electrically activated latching fingers spaced at 15 deg intervals around the periphery of the forward frame to assure uniform distribution of loading.

Tug/Shuttle Docking Mechanism

The docking mechanism consists of a built-up 2024 aluminum base bracket which bolts to the aft bulkhead of the cargo bay, a machined 2024 aluminum pivot lever, two hollow A-286 stainless pivot rods with machined aluminum 2024 end fittings and external ball bushings, a dual electric actuator and manual actuator release and override provisions. The pivot lever is pin-connected between the base bracket and the aft frame of the base ring and the actuator is pin-connected between the lever and the base bracket. The two pivot rods are also pin-connected to the base bracket. The pivot mechanism is only stiff enough structurally to provide controlled entry of the Tug into the Shuttle cargo bay in a weightless environment. This relative flexibility prevents the mechanism from structurally coupling with the main interface attachments.

The base ring is a 165 cm (65 in) long cylindrical honeycomb sandwich shell with a 208 cm (82 in) outside radius. Its primary function is to provide Tug attachment to the Shuttle, accepting concentrated loads at the Shuttle

interface and shearing them out to a near-uniform load at the Tug interface. Major structural frames are located at each end of the shell and two stability frames are spaced between.

Interface Panels

All fluid and electrical interfaces between the Tug and the Shuttle are accomplished through two interface panels that are located near the aft end of the vehicle. These panels are approximately 50.8 x 86.4 cm (20 x 34 in) in size. The fluid interfaces are LO_2, LH_2, GO_2, GH_2, steam vent, and He fill and drain. The fluid disconnects are similar to those used in the Saturn V program. A dynamic (pressure sensitive) seal serves as the mating seal. A highly polished probe engages the lip seal and any pressure increase provides a corresponding increase in the force applied between the lip seal and probe. This feature reduces leakage rates at the disconnect interface. Each half of the disconnect contains a shut-off poppet. After the probe engages the mating seal, continued axial motion causes both poppets to move to a full open position allowing fluid flow. When the units are disengaged, the poppets close prior to the probe disengaging from the mating seal. This failure eliminates hard poppet seating and reduces the amount of residual fluids trapped between the two halves of the disconnect.

The electrical connectors can withstand large amounts of misalignment between the plug and receptacle and still be capable of reliably mating and unmating without inducing damage to either the pin or socket contacts. This is accomplished by self-alignment keys and keyways and specially designed contacts that prohibit engagement until the connector shells have been accurately aligned. In order to compensate for longitudinal overtravel, the receptacle floats in the carrier plate to which it is mounted and is provided with an interfacial sealing between the plug and receptacle. This permits up to 1.3 cm (0.50 in) of overtravel during the mating process. The physical size of these connectors is anticipated to be comparable to a No. 24 shell size connector of the MIL-C-26482 variety.

Propellant Tanks

The propellant supply system consists of two tanks, a liquid hydrogen tank with a capacity of approximately 3901 kg (8600 lb) LH_2 at 21^{o}K (37^{o}R) and a liquid oxygen tank with a capacity of approximately 22,680 kg (50,000 lb) at 91^{o}K (163^{o}R). The LH_2 tank is 4.4 m (14.5 ft) in diameter and 5 m (16.45 ft) in length with a cylindrical section of length 1.9 m (6.19 ft) and two elliptical domes of height 1.6 m (5.13 ft). The LO_2 tank is 3.9 m (12.78 ft) in diameter and 2.8 m (9.04 ft) in length composed of two $\sqrt{2}$ elliptical domes. The tanks are made from 2219-T87 aluminum alloy ranging in thickness from 0.05 cm (0.02 in) at the dome to 0.10 cm (0.04 in) in the sidewall.

Propellant Tank Insulation System

The function of the propellant tank insulation system is to thermally isolate the propellant tanks from the outside environment to prevent excessive propellant boil-off.

The tank insulation system basically consists of a multilayer superinsulation, a purge bag enclosing the insulation, and vent valves to vent the insulation and purge bag. The multilayer insulation (MLI) is Double Goldized-Kapton (DGK) with spacers separating the individual layers. DGK was selected as the basic insulation because gold is more inert than aluminum (which is the more commonly used surface material) and therefore is expected to last longer. Kapton was selected because of its favorable high temperature characteristics. The insulation proper is attached to the external surface of the propellant tanks under the insulation purge bag and the meteoroid shield.

During periods of tanking and ground hold, the MLI system must be protected to prevent the formation of damaging condensates. Therefore, the insulation blankets are encased within a purge bag. Prior to tanking, the insulation volume between the bag and tankage is purged with helium to remove the condensates. Once the condensates are displaced, the helium

purge is continued throughout the tanking and ground-hold phase to prevent the atmosphere in the Shuttle cargo bay from liquifying. The reflective sheets of the MLI system are perforated (about 1 percent of the layer area) to enable evacuation of the ground purge helium during ascent.

The insulation blankets are also purged during reentry. The function of the reentry MLI purge system is twofold. First, it provides a slightly positive pressure within the MLI which prevents damaging compressive loads between the reflective sheets and spacers. Second, it prevents condensibles from entering the blankets (the tanks may be at cryogenic temperatures during reentry, dependent upon the mission profile) which would result in deleterious ice formation. The helium is routed through the MLI blankets through the manifolded tubing which is also used to route the ground purge gases from the MLI. During reentry, ambient pressure sensing devices are used to keep the pressure within the MLI about 3450 N/m^2 (0.5 psi) above the ambient pressure.

The purge bag which encloses each of the propellant tanks and insulation blankets is made of Kapton approximately 0.38 cm (150 mil) thick. The Kapton is coated on its outer surface with gold and on its inner surface with teflon. The bag is modular so that it can be zippered onto the tanks in sections.

The vent valves permit venting of the purge bag and insulation in orbit. They remain closed during ground hold, and open and vent during ascent and in orbit. Additionally, they close during descent and permit back filling of the insulation. The valves are circular aluminum poppet valves with polymeric seals which are normally open. They are attached to the structure at the structure/purge bag interface. Each valve (there are three on the hydrogen bag and two on the oxygen bag to provide a redundant system) is of integral construction and can be removed and replaced as an integral unit.

Main Propulsion System

The main propulsion system is composed of four separate subsystems, the main engine subsystem, the propellant feed subsystem, the propellant tank pressurization controls, and the thrust vector control subsystem.

Main Engine Subsystem

The main engine subsystem is composed of a single 88,960 N (20,000 lb) thrust staged combustion engine utilizing hydrogen and oxygen as propellants. The engine has been developed with a capability of providing 5:1 throttling and operating at varying engine mixture ratios for propellant utilization purposes. During its operation, it is required to provide makeup pressurant to replace the propellants drawn from the propellant tanks. To provide this function, the main engine subsystem contains heat exchangers which vaporize hydrogen and oxygen to provide the necessary makeup pressurant gases. Pressurization prior to main engine start is provided by the auxiliary propulsion system (APS) as will be described in the next section.

The engine incorporates an engine control unit which adjusts engine operating conditions to insure safe operation during variations in thrust and mixture ratio. It is anticipated that the output of the instrumentation for the main engine subsystem would be fed into an onboard flight recorder and used in subsequent functional analysis.

The main engine is shown schematically in Figure IV-3. It is referred to as a staged combustion cycle because it pre-heats the major portion of the fuel supply by reacting it with a small amount of liquid oxygen in the pre-burner, and utilized these heated gases to drive the turbine. After leaving the turbine, the gases are ducted into the main combustion chamber where they are combusted with the remainder of the oxygen and expanded through the nozzle to provide thrust for the vehicle.

From the hydrogen tank, the fuel flows through a vacuum jacketed duct into a low speed inducer on the front of the hydrogen pump assembly. The low speed inducer allows the hydrogen pump to operate at very low values

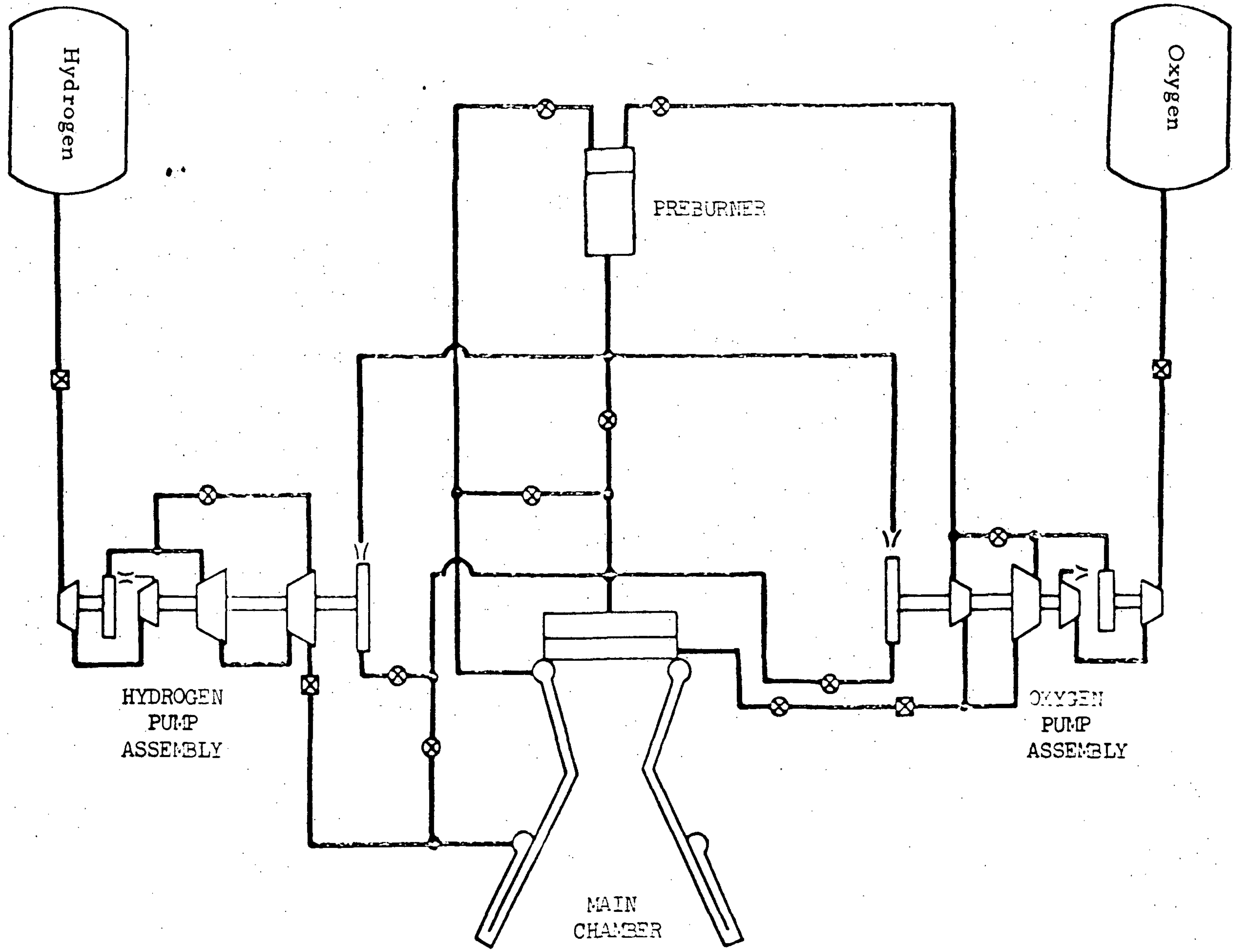

Figure IV-3. Typical Engine System Schematic

of hydrogen NPSH. From the low speed inducer it flows into the first stage of the main hydrogen pump assembly. The major portion of the hydrogen leaving the second stage of the hydrogen pump is first utilized as coolant in the regeneratively cooled main thrust chamber. On leaving the thrust chamber, it enters the pre-burner assembly where it is heated by reacting with a small percentage of liquid oxygen. The other portion of the hydrogen leaving the second stage of the pump is utilized for cooling the pre-burner walls, for cooling the bearings in both turbopump assemblies and for cooling various structural components in the engine system. It is returned into the main flow downstream of the turbine discharge. The main flow then enters the main chamber for reaction with the remainder of the liquid oxygen.

The liquid oxygen leaving the main propellant tank enters a low speed inducer which serves a similar function to the hydrogen low speed inducer assembly. From the inducer the oxygen enters the two-stage oxygen pump. The high pressure liquid oxygen leaving the second stage of the pump is used for pre-burner feed while the oxygen leaving the first stage of the pump assembly is utilized in the main thrust chamber assembly.

Engine control is achieved through the use of a number of flow control valves. The primary control is achieved by regulating the oxygen flow to the pre-burner. Various other fuel valves and a main chamber oxidizer valve are required to balance the system to insure safe operation. The complexity of the mixture ratio control and thrust control requirements dictate the use of a computerized engine control unit. It also requires extensive instrumentation and control functions within the engine.

Propellant Feed Subsystem

The propellant feed subsystem is composed of a series of ducts which provide for the transportation of propellants between the propellant tanks and the main engine system. It is also used for filling, draining and dumping operations between the main tank, engine, and the exterior of the vehicle.

These lines are relatively long and, in the case of the liquid hydrogen, are vacuum jacketed to prevent excessive boiloff. Both main propellant lines contain provisions for insuring that liquid propellant is delivered to the engine inlets.

Propellant Tank Pressurization Controls

The function of propellant tank pressurization during main engine burn is provided by heat exchangers which vaporize the liquid propellants. The required propellant tank pressure level is controlled by a combination of solenoid valves, pressure switches and orifices.

Thrust Vector Control Subsystem

The thrust vector control subsystem provides the actuation forces necessary to move the main engine chamber to achieve yaw and pitch control during main engine operation. It is composed of a dual hydraulic pump system with dual servovalves and hydraulic actuators for the yaw and pitch planes. It also includes the associated tubing required to duct the fluid from the pump to its point of usage.

Auxiliary Propulsion System

The auxiliary propulsion system (APS) supplies the required thrust and total impulse to provide the following functions:

1. Maintain Tug vehicle attitude control throughout the coast phases of the mission.
2. Perform Stage ΔV maneuvers for mid-course corrections.
3. Perform transverse and lateral translation maneuvers during rendezvous and docking.
4. Perform vehicle and sensor pointing and alignment as required.
5. Provide roll control during main engine burns.
6. Provide ΔV for propellant settling.

7. Provide reactants for fuel cell operation.

8. Supply gases (GO_2 and GH_2) for pressurization of main propellant tanks prior to main engine main stage operation.

9. Provide a thermodynamic vent cooling subsystem.

These functions are performed by the APS in orbit after removal of the Tug from the Shuttle cargo bay. To perform the functions, the propellant conditioning systems of the APS convert LH_2 and LO_2 from the auxiliary tanks in the Tug main propellant tanks into GH_2 and GO_2, and supply them to the using systems.

The APS was designed to meet fail-safe safety criteria. In addition, the APS supplies liquid propellants to the main engine during the idle mode start sequence and liquid hydrogen for feedline and APS turbopump cooling. Gaseous propellants are provided from the APS accumulators for repressurizing the main tanks prior to a main engine burn and for fuel cell use.

Figure IV-4 is a block diagram which shows the relationship of the major elements of the APS and its functional interfaces. The APS is described by referring to Figure IV-4 and following the propellant flow paths starting at the propellant tanks.

Propellant Tanks

The APS propellant is stored in separate tanks located within the main propellant tanks. The APS tanks are considered part of the main tank system rather than part of the APS. The APS tanks require a separate pressurization system and must provide propellant feed during zero gravity and against adverse accelerations from the APS thrusters. The APS tanks also provide chill-down propellant for the main engine and the APS propellant conditioning system.

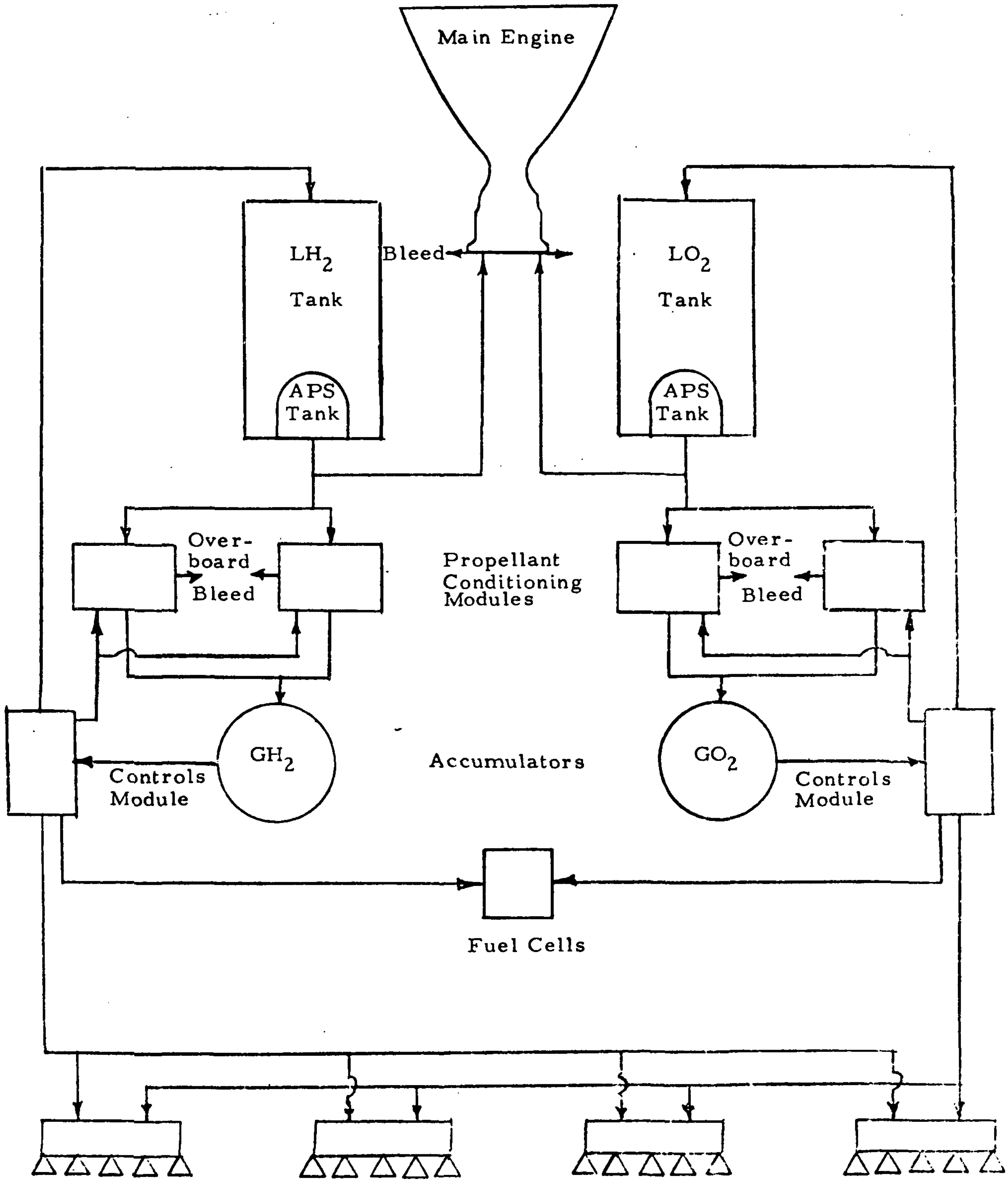

Figure IV-4. Tug Auxiliary Propulsion System Block Diagram

Propellant Conditioning Modules

There are two propellant conditioning modules for each propellant to provide redundancy. Each propellant conditioning module receives low pressure liquid propellant from the APS tanks and delivers the propellant to the accumulators as high pressure, relatively warm gas. To accomplish this function, each propellant conditioning module contains the following assemblies:

1. Propellant pump to increase propellant pressure and pump propellant through the conditioning system.

2. Turbine to drive the pump. The turbine is driven by hot gas from the gas generator. The turbine exhaust gas is vented overboard.

3. Heat exchanger to gasify and heat the liquid propellant. The heat is derived from the gas generator gases. The exhaust gases are vented overboard. An overboard bleed is also used on the cold side to assure that liquid is in the heat exchanger before the hot gas is allowed to flow to reduce thermal excursions and prevent heat exchanger burnout.

4. Gas generator to provide hot gas for the heat exchanger and turbine. The gas generator burns gaseous oxygen and gaseous hydrogen. The gas generator propellants are supplied from the APS accumulators. The propellant is pressure-regulated for the gas generator in the controls module.

APS Accumulators

The accumulators store the propellants as pressurized gases for distribution to the thrusters, gas generators, main tanks and fuel cells.

Controls Modules

The controls modules contain valves, pressure switches, regulators, relief valves and servicing ports for control of the APS feed system. The

functions of a control module are: to provide pressure-regulated propellant to the thrusters, gas generators, fuel cells and main tanks; to provide pressure control of the accumulators by signaling the on and off operation of the propellant conditioning system.

Thruster Modules

The thruster modules provide reaction control forces as commanded by the attitude control electronics. There are four thruster modules, each containing five thrusters. The thrusters provide 445 N (100 lb) thrust each by burning gaseous oxygen and hydrogen. The propellants are ignited by an electric spark igniter. The thrusters can provide a lower thrust of 89 N (20 lb) by flowing gaseous hydrogen only for fine attitude control or station-keeping of the Tug.

Electrical Power

The electrical power subsystem consists of two fuel cell power plants and associated distribution and control elements capable of providing nominal 28 V dc power for the Tug subsystems. Gross characteristics of the system pertinent to the refurbishment study objectives include:

Average Power - 300 Watts

Weight - 77.1 kg (170 lb)

The fuel cell on which these data are based is projected to come from a fuel cell technology program being conducted by NASA.

Avionics

The avionics system consists of the Guidance Navigation and Control Subsystem, the Rendezvous and Docking Subsystem, the Data Management Subsystem, Checkout and Fault Isolation (COFI) Subsystem, Subsystem Management and the Communications Subsystem.

Guidance Navigation and Control Subsystems

This system consists of: three strapdown IMUs similar to the Autonetics MICRON electrostatic unit; an edge tracking horizon sensor with four heads; two strapdown star trackers; and a control electronics assembly which provides the interface between the guidance computer (of the Data Management Subsystem) and the propulsion system.

The equipment selected is of mature status with the exception of the MICRON IMU. This component is being developed under an Air Force contract for the Air Force Avionics Laboratory and is expected to be available consistent with Tug planning. Nevertheless, substitution of alternate candidates (such as the Dodecahedron IMU), if required, should have only a minor effect on the refurbishment study results and conclusions.

Rendezvous and Docking Subsystem

The sensor used for Tug rendezvous and docking is the Scanning Laser Radar presently under development by ITT. For redundancy, a second unit will also be employed. Essential parameters are:

Weight/unit - 13.6 kg (30 lb)

Power - 20 Watts

NASA/MSFC has previously sponsored engineering feasibility development of this system, including prototype testing by ITT and Martin Marietta. The specific design required for the Tug will result from an extension of that effort and appropriate design changes commensurate with Tug requirements.

Data Management System

The system is composed of three LSI computers derived from the Control Data Corporation (CDC) 469 (representative of a class of LSI computers available). The plated wire main memory is 40K words, the word size is 32 bits, and a floating point arithmetic is used. The units are in a

triply redundant configuration where the outputs are constantly compared and voted in a fourth unit (the voter). The data management subsystem is interconnected with the complete avionics system via a data bus. The data bus is controlled by an internally redundant Bus Control Unit. Individual sensors are connected to the data bus via Data Bus Adapters. A plated wire mass memory unit of 10^7 bit capacity is provided for software storage and growth capability.

The technology for the data management subsystem is mature, but the specific system components and the program for the required redundancy management, checkout, et al., will need design and development.

Checkout and Fault Isolation (COFI)

The COFI subsystem will provide checkout and fault isolation to allow for automatic switching of failed functional paths and to isolate indicated failures. The COFI program will use results of limit testing by the executive program and unique calculations and logical decisions by the subsystem programs.

The fault isolation program is not scheduled under normal program operating conditions but is scheduled by the executive or the subsystem program when a fault is detected. Before scheduling the fault isolation program, the executive will load the required COFI diagnostic routines and supporting failure data from mass memory. A diagnostic routine for critical failure evaluation will normally be maintained in the main core program.

The COFI program will provide for unique diagnostic routines with a maximum mass memory storage of 4000-16 bit words per routine. The diagnostic routines will provide for the isolation and automatic switching of time-critical functional paths.

The COFI program will perform trend tests and reasonableness tests as required to assure the integrity of the Tug system. Trend tests will be designed to predict failures from historical data. Reasonableness tests will be designed to evaluate system response to applied stimuli.

The COFI program will provide for the display of failure data on demand by the AGE operator. Display capability will include the first and second sets of failure and supporting failure data. Data will be transmitted to CRT displays by the display and control program.

Subsystem Management

The subsystem management program will provide for all computer-controlled required subsystem functions not provided for by the executive, displays and controls, flight control, COFI, or sequencing programs. The subsystems programs are defined as follows:

Vehicle structures

Thermal protection

Main propulsion

Orbital maneuvering

Attitude control propulsion

Cryogenic tanks

Communications

Electrical power

Hydraulic power

Environmental control

Payload

Docking

Shuttle mating and separation.

Communications Subsystem

The communications subsystem provides the capability for secure communications between the Tug and the Space Tracking and Data Network

(STDN) and between the Tug and the Shuttle. This capability is provided by an S-Band system. The selected equipment is currently available in heavier weight design.

D. SCHEDULED MAINTENANCE TASKS

Three levels of maintenance have been defined for the scheduled maintenance function: (1) routine inspection; (2) engineering inspection, and (3) replace or refurbish. The "routine inspection" is performed after each mission and usually consists of a visual inspection, minor calibration, leak checks, etc. The "engineering inspection" is performed less frequently and usually consists of disassembling the system into its major components and a more detailed inspection than that performed during the routine inspection. The "replace or refurbish" maintenance level usually consists of removing the system from the vehicle and replacing it with a new or refurbished item. To assist in establishing the frequency at which each level of maintenance would be performed, the Tug flight regime was divided into three phases. Phase I represents the flight test program and consists of the first 5 flights. Phase II represents the initial operational capability (IOC) and consists of the next 20 flights. Phase III is the mature operational capability (OC) which begins after Phase II. For each of the eleven major vehicle areas described in the previous section, the three levels of maintenance were defined to the depth necessary to permit an estimate of the manpower and hardware requirements for Tug maintenance. The maintenance tasks are described in the following sections. These tasks are summarized in the "refurbishment operation sheets" which are presented in Appendix I.

Basic Structure

The scheduled maintenance of the basic structure consists mainly of visual inspections. There is no planned refurbishment. Table IV-1 shows the proposed maintenance frequency.

Table IV-1. Scheduled Maintenance Frequency

Basic Structure

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	2, 4	Every Flight	Every Flight
Engineering Inspection	1, 3	3, 6, 15	5, 15
Replace/ Refurbish	5	10, 20	10, 20

* No. of flight after which the maintenance level is performed.

The maintenance crew is made up of the following personnel:

Engineers	-	1
Technicians	-	2
		3

Routine Inspection

Routine inspection of the basic structure consists of a visual inspection for apparent structural damage. Twenty-four manhours is the estimated manpower required for this task.

Engineering Inspection

An engineering inspection is performed whenever the propellant tank insulation system is removed from the tanks. The maintenance level is simply a more detailed visual inspection of the basic structure since the removal of the insulation system exposes more of the basic structure than is normally visible. Forty-eight manhours have been estimated for this task.

Replace/Refurbish

The title "replace/refurbish" is a misnomer in regard to the basic structure since the replacement or refurbishment of the basic structure is never scheduled. The tasks involve the same effort as required in the engineering inspection with the addition of x-raying and ultrasonic testing in selected areas. The manpower estimate for this maintenanance level is 72 manhours.

Meteoroid Shield

The proposed maintenance frequency of the meteoriod shield is shown in Table IV-2. The maintenance crew is the same as the basic structure crew and is made up of the following:

Table IV-2. Scheduled Maintenance Frequency
Meteoroid Shield

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase II (OC) Operational >20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	-	-	-
Replace/ Refurbish	5 (50%)	10, 20	10, 20

* No. of flight after which the maintenance level is performed.

Engineers	-	1
Technicians	-	2
		3

Routine Inspection

The meteoroid shield is removed after every flight to allow inspection of the propellant tank insulation system. A visual inspection of the shield is performed. Sixty manhours are estimated to perform the visual inspection of the shield and the removal and replacement.

Engineering Inspection

There is no engineering inspection maintenance level depicted for the meteoroid shield.

Replace/Refurbish

This task is the same as the routine inspection except the old shield is replaced with a new shield. At the end of the flight test program, it is assumed that 50 percent of the shield will require replacement. The effort required for this task is 60 manhours.

Tug/Payload Docking Mechanism

The docking mechanism maintenance schedule is shown in Table IV-3. The same maintenance crew is used as for the basic structure and consists of the following:

Engineers	-	1
Technicians	-	2
		3

Routine Inspection

Routine inspection consists of a visual inspection and functional checks of the latches and shock absorbers. This maintenance level is accomplished with 24 manhours of effort.

Table IV-3. Scheduled Maintenance Frequency
Tug/Payload Docking Mechanism

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	-	-	-
Replace/ Refurbish	5	10, 20	10, 20

* No. of flight after which the maintenance level is performed.

Engineering Inspection

None

Replace/Refurbish

The docking mechanism is removed from the vehicle and refurbished at an estimated cost of 25 percent of the unit cost. After reinstallation of the system, a routine inspection is performed. Forty-eight manhours are required to remove, replace and inspect the system.

Tug/Shuttle Docking Mechanism

The maintenance task description for the Tug/Shuttle docking system is the same as for the Tug/payload system. The maintenance schedule is shown in Table IV-4. The maintenance crew is the same as for the basic structure.

Engineers	-	1
Technicians	-	2
		3

Routine Inspection

This maintenance level consists of a visual inspection and functional checks of latches and shock absorbers. The estimate of the effort involved is 24 manhours.

Engineering Inspection

None.

Replace/Refurbish

The docking system is removed, refurbished, replaced and a routine inspection performed. The effort required to remove, replace, and check out is 48 manhours. The system is refurbished at a cost of 25 percent of the unit cost.

Table IV-4. Scheduled Maintenance Frequency Tug/Shuttle Docking Mechanism

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	-	-	-
Replace/ Refurbish	5	10, 20	10, 20

* No. of flight after which the maintenance level is performed.

Interface Panels

Table IV-5 shows the maintenance schedule for the interface panels. The maintenance crew is the same as for the basic structure and consists of the following:

Engineers	-	1
Technicians	-	2
		3

Routine Inspection

This maintenance function consists of a visual inspection for apparent structural damage and physical alignment. Twelve manhours have been estimated to perform this task.

Engineering Inspection

A routine inspection is performed in addition to the replacement of connectors, O-rings, etc. Thirty-six manhours are assumed to be required for this task. Hardware costs are assumed to be 10 percent of the unit cost.

Replace/Refurbish

The panels are removed and replaced with new panels. A routine inspection is then performed. The effort involved is 36 manhours.

Propellant Tanks

The scheduled maintenance frequency for the propellant tanks is shown in Table IV-6. The maintenance crew consists of:

Engineers	-	1
Technicians	-	3
		4

Table IV-5. Scheduled Maintenance Frequency
Interface Panels

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	1, 3	5, 15	-
Replace/ Refurbish	5	10, 20	10, 20

* No. of flight after which the maintenance level is performed.

Table IV-6. Scheduled Maintenance Frequency

Propellant Tanks

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	-	-	-
Replace/ Refurbish	5	20	20

* No. of flight after which the maintenance level is performed.

Routine Inspection

This level of maintenance is performed after every mission and consists of a visual inspection, a leak check and a helium sniff test. Successful completion of this maintenance is considered proof of structural adequacy for the next flight. The manpower estimate for this maintenance level is 128 manhours.

Engineering Inspection

None.

Replace/ Refurbish

For the operational flight phase, the propellant tanks are replaced after 20 missions. The manpower required for a complete tank replacement has been estimated at 1100 manhours. The details of the effort required are contained in Appendix I.

Propellant Tank Insulation System

The information included in this section is the current best estimate of the refurbishment requirements for the propellant tank insulation system. This estimate is based on available information from the literature, conversations with individuals in industry who are intimately associated with development and testing of multilayer insulation systems, and on the interpretation of the accuracy of technological predictions based on historical data for space subsystems.

It is well recognized that MLI is the most attractive category of insulation for long-term space protection of cryogenic propellants. This has resulted in the development of various polymeric substrates, metalized surfaces, and insulation separators. Initially, most MLI were aluminized Mylar with various types of spacers such as dacron tufts and dacron melting. The major difference between the various MLI was in the spacer material and not in the metalized shield.

Because of the reusability requirement and the orbiter payload bay venting environment, a second generation MLI consisting of goldized Kapton with a yet undefined dacron spacer was selected for this application. A goldized surface was selected because of its stability when exposed to normal atmosphere and its attendent contaminants, and Mylar was replaced with Kapton because of its higher operational temperature limit. Goldized Kapton is currently being developed under NASA sponsorship by General Dynamics/Convair (GD/C) and McDonnell Douglas Astronautics (MDAC).

The tank insulation system consists of three distinct subsystems: the insulation blankets, the purge bay, and the vent valves. The main problem with the insulation blankets will probably be the separation of the insulation due to vibrational forces. The pins and joints will begin to loosen and the metalized surface will begin to separate from the substrate. At the beginning of the operational phase of the program, the insulation should be removed and reconstructed after every five missions. The total life of this insulation is estimated to be approximately 20 missions. Total life will be limited by the number of times that the insulation can be reconstructed. As the vehicle matures with increasing number of flights, the number of flights between overhauls should increase; however, the extent to which it can be increased is not known. (The current ultimate objective of insulation life for this type of application is approximately 100 flights.)

The most obvious problem with the purge bag is its inability to contain the purge gas. This will result in insulation contamination and possibly insulation crushing. Over-pressurization due to a pressure regulator failure in the purge system may result in a bag failure. The sealing requirement on the bag is not a critical item. Leakage is permissible and in all practicality cannot be prevented. However, leakage should be kept to a minimum. A major overhaul (by replacement) should be done every 20 missions.

The most critical problem with the vent valve system is a failure in the closed position which will result in reduced or non-venting of the

insulation. Should this happen, the boiloff will be excessive. Bursting of the purge bag is possible but not probable because of the redundant valves and the probable use of a relief valve. The valve failure in the open position will result in non-purging. If this should happen on the ground, the valve can be fixed; if it were to happen on reentry, the insulation will be damaged and will have to be repaired. The causes of failure are valve wear, valve actuator failure, and valve opening failure.

Maintenance Crew

The scheduled maintenance frequency is shown in Table IV-7. The maintenance crew is made up of the following:

Engineers	-	1
Inspectors	-	0.5
Technicians	-	<u>4</u>
		5.5

Routine Inspection

Prior to commencement of any maintenance level, the flight data are analyzed to determine if the thermal system has performed properly. Some of the items which should be noted are the propellant boiloff rate, insulation pressure history during ascent, insulation outgasing during the actual flight, and the back-filling pressure history during descent. The evaluation of these data will give an indication of the magnitude of the probable maintenance effort which will be required. An estimate of the test points is given in Appendix I. The meteoroid shield, which is located external to the thermal protection system is removed. The purge bag is then inspected visually for defects. Primary attention should be directed to the attachment of the bag to the structure, and the bag/valve attachments. If the bag is defective, it is removed from the vehicle and either repaired or replaced. While the bag is being repaired, the vent valves are inspected.

Table IV-7. Scheduled Maintenance Frequency
Propellant Tank Insulation System

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	1, 3	3, 6, 15	5, 10, 15
Replace/ Refurbish	5	10, 20	20

* No. of flight after which the maintenance level is performed.

This consists of inspecting the seating action, valve spring tension, and the valve relay actuators. If any defects are found, the valves are removed and sent to repair. If the purge bag is still on the vehicle at this time, it is unzipped to expose the insulation.

Insulation inspection consists of both visual and laboratory inspection. Visual inspection consists of inspecting the insulation for obvious damage which can be detected visually. This consists of inspection for tear, compression, etc. The second level of inspection consists of using laboratory instrumentation to evaluate insulation condition. The availability and use of this class of instrumentation is presently uncertain. There are no existing techniques of insulation performance evaluation without subjecting it to a thermal vacuum test. A development program is required to provide a reliable evaluation technique within the 1980 time frame. Several different testing techniques have been suggested such as X-ray scanning, IR sensors, and electrical resistance and capacitance; however, investigation into the applicability of these techniques is not sufficiently advanced to even make an estimate of the potential use of these methods.

If tests indicate that the insulation is defective, it is removed and either sent back to the vendor or repaired in the maintenance area, depending on the type of repair that is required. The removed insulation is replaced with reconditioned insulation. It is then tested for thickness, lay, and any other parameters which may be developed between now and 1980 which will give some indication of insulation performance. If the insulation does not pass these tests, it is reinspected and repaired as necessary. After the insulation is determined to be acceptable the purge bag and vent valves are replaced. The valves are then exercised to determine that they are operating properly. At this point, the thermal system is completely put together. The purge bag is now back-filled and checked for leaks.

The manpower estimate for routine inspection is 64 manhours. This does not include 48 manhours that are required to remove and replace the meteoroid shield. This manpower is accounted for under meteoroid shield maintenance.

Engineering Inspection

During Engineering Inspection, the multilayer insulation is removed and replaced with reconditioned insulation, regardless of its apparent condition. The rationale for requiring the replacement of the insulation during engineering inspection is that the estimated life of a reusable insulation blanket is purely conjecture. There has not been any testing of any consequence on the reusability of MLI for Tug application. There has been some testing of the compressibility and resilience of sample insulation blankets; however, no testing of insulation vibrational wear has been performed. Secondly, the availability of a reliable test technique is questionable; without a testing technique, the subsystem will have to be replaced more often than would be the case if the system could be tested to determine its condition. Currently it is estimated that an engineering inspection will be performed every 5th mission.

The manpower requirement for this inspection level is approximately 682 manhours. This is significantly higher than the requirement for routine inspection because of the time consuming process of insulation removal and reinstallation. The multilayer insulation system is sent back to the factory for reconditioning. Since insulation reconditioning requires disassembling the blanket and reforming it, the overhaul cost will be a relatively large fraction, approximately 60 percent, of the initial cost.

In addition to the manpower and hardware cost identified above, the vehicle will be put in a vacuum chamber to check out the installation of the reconditioned tank insulation system. The vacuum requirement for this test is 10^{-3} Torr and the cost has been estimated at $15,000. The estimated cost of the vacuum test is itemized in Appendix I.

Replace/Refurbish

The main difference between the engineering inspection maintenance and the replace/refurbish level is that, for the latter level, the insulation system is replaced with a new system rather than one that has been

refurbished. In addition, the purge bag and vent valves are replaced. The replace/refurbish maintenance level is performed every 20 missions due to the limitation of the refurbishability of the MLI. The effort required has been estimated at 776 manhours. The increase over the engineering inspection level of maintenance is due to the time involved with removal and replacing of the purge bag and vent valves.

The total hardware cost is estimated to be the cost of a new tank insulation system, \$300,000. In addition, a vacuum test will be performed at a cost of \$15,000 to check the installation of the MLI.

Main Propulsion System

The maintenance approach for the engine system is dependent upon a number of operational decisions. The first of these is concerned with the state of development of the main engine at the time it first begins flight operations. It is possible in the ground development program to conduct extensive ground testing to thoroughly demonstrate the durability characteristics of the main engine. It seems prudent to follow the airline development philosophy of starting flight operations when the engine has completed a preliminary flight rating test program. This development is then continued both on the ground and in flight until the engine reaches a fully operational stage. The space Tug engine with its durability requirement of 20 missions or 300 thermal cycles would require a tremendous amount of ground testing to prove that the design was adequate for the desired durability.

Obviously, the airline approach cannot be followed completely since the space Tug vehicle does not possess engine-out capability. However, the general approach can be followed if conducted in a conservative manner which precludes a full engine failure in flight, but which allows the development of engine operating history under actual operating conditions. This sort of development philosophy decreases the time and cost of a development program substantially but does increase the inspection and overhaul costs of the flight program. It also requires that procedures be taken to

sense incipient failure of any one of the critical engine components. With this information, the engine may be refurbished prior to operation, or if such deviations are sensed by the onboard system, the engine operation may be changed to more benign conditions to preclude an in-flight failure.

In utilizing such an in-flight demonstration program, it is necessary that a number of extra measurements be taken within the engine system to characterize the functional characteristics of the critical engine components. This history, compiled over a number of flights, establishes normal signature characteristics for the engine, and deviations in these functional characteristics are an indication of incipient failure.

The requirement for reusability of the engine system requires a number of changes in the engine design approach. The first of these is the use of an on-board checkout system. A number of checkout procedures on an engine fall in the category of continuity checks of circuitry and functional checks of various components. The use of an onboard checkout system adapted from normal flight controls and flight checking procedures eliminates the need for much ground equipment. For maximum safety in operation, and for minimization of maintenance requirements, the onboard system should have capability of performing functional characteristic comparisons during engine operation to determine whether the engine operating conditions should be changed to preclude possible failure.

The requirements bring about the necessity for making a large number of measurements within the main engine subsystem during flight operations. The requirements for engine control, safety, and for flight reconstruction are outlined in Appendix I. Each of the measurements has been related to various functions during flight and ground operations. The control function has to do with engine control of mixture ratio and thrust changes. Redline functions are concerned with limiting temperature, pressure, or speed to safe operating levels. The monitoring functions permit the onboard flight computer to characterize the functional characteristics of the various parts

of the engine system, and can also be used for flight failure analysis and reconstruction. The ground checkout measurements are needed to perform routine maintenance and pre-flight checkouts.

Another design feature intended to enhance maintainability of the engine is that of modular replacement of components and sub-components. This study has assumed modular replacement and a minimum of teardown and disassembly at the launch site. It has been assumed for purposes of this study that these components would either be replaced and discarded or sent back to a factory for rework if repair was feasible.

In keeping with the philosophy noted earlier, it is intended that the operation of the vehicle will provide demonstration of the capabilities of the engine to operate over extended periods of time and under repeated duty cycles. In any flight program, it is necessary to proceed cautiously during the initial flight phases to insure satisfactory operation of all components. The approach taken herein is to conduct an engine teardown inspection at increasing time intervals as the flight program proceeds. These engineering inspections are not intended for refurbishment or overhaul but are only intended to provide information concerning the wear and operating characteristics of all the various components of the engine. It is intended that parts will be replaced during engineering inspection only as necessary and that the original schedule of inspection and the overhaul operations would be modified in accordance with the results of the engineering inspections. If a component is found to be wearing out earlier than anticipated, that component should be improved and the engine inspections would continue at frequent intervals until the improved component was installed in the engine.

An overhaul performed during the replace/refurbish maintenance cycle is considered an operation wherein major parts of the engine are replaced or reworked as necessary to bring it to a new condition. Since these operations provide insight into the maturity level of the engine, it is planned that the engineering inspections and the overhaul operations will be performed by factory personnel at the factory. For this reason, only a small maintenance

crew is needed at the launch site. The maintenance crew must be able to remove the engine from the vehicle and package and ship it to the factory for the necessary work.

A tentative schedule of maintenance levels has been established assuming normal progression of the engine demonstration and is shown in Table IV-8. Note that the first engineering inspection is made after the first flight. There is concern that the flight environment will be substantially different than the ground test environment because of vacuum conditions and vehicle-imposed stresses, and it is recommended that the engine be completely disassembled and inspected after the first flight. The time between engineering inspections increases during the flight operations until in Phase III only one engineering inspection is performed between overhauls. It is anticipated that late in the operational phase of the program there would be no engineering inspection between overhauls and that the normal routine inspections would suffice.

Maintenance Crew

The maintenance crew required for main propulsion system maintenance is composed of the following personnel:

Engineers	-	1
Inspectors	-	1
Technicians	-	6
Analysts	-	1
		9

Routine Inspection

Routine inspection includes a review of the flight data, various functional tests, pressure tests, structural integrity tests, alignment checks and calibration tests that are required to insure that the engine is flight-ready. The operations and the equipment required for routine maintenance and the base crew activities for engineering inspection and replace/refurbish operations are shown in Appendix I. It is estimated that approximately

Table IV-8. Scheduled Maintenance Frequency
Main Propulsion System

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational > 20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	1, 3	7, 13	10
Replace/ Refurbish	-	2, 20	20

* No. of flight after which the maintenance level is performed.

189 manhours will be required to perform routine maintenance on the main propulsion system.

Engineering Inspection

This maintenance cycle includes a review of the flight data, removal of the main engine for teardown inspection and performance of a routine inspection after the main engine has been reinstalled on the vehicle. The engine teardown is performed at the factory at a cost of 6 percent of the unit cost. Approximately 441 manhours are required on-site for engineering inspection.

Replace/Refurbish

Same as engineering inspection except the hydraulic components, control system valves and propellant ducting are also removed. The refurbishment of these equipments is done at the factory for 25 percent of the unit cost. Approximately 621 manhours are required on-site.

Auxiliary Propulsion System

Within the past experience of launch and space vehicles, failure of the APS has not been a major cause of hardware replacement because of the one-shot nature of the missions. Hardware is generally replaced when out-of-tolerance conditions are noted during extensive testing procedures. The allowable tolerances are always very tight to attain extremely high "one-shot" reliability. For the purpose of this presentation such out-of-tolerance conditions are included as random failures.

Based on past experience, hardware is generally replaced prior to "one-shot" flight for the following reasons:

1. Out-of-tolerance condition during checkout.
2. Hardware purge for suspected deficiency. For instance, if a manufacturing deficiency is noted in a single component, all components of the same lot are removed for inspection or arbitrarily scrapped.

3. Excess calendar life. The best known example is the elastomeric O-ring life limitation.

4. Operational error. It is not uncommon for systems to be refurbished because they have been subjected to non-design environments such as fluid system contamination, excessive voltage, extreme temperature, shock (hit with a dropped wrench), etc.

5. Design changes. Hardware design is generally in a continual state of evolution and some design changes become mandatory as a function of operational experience. Such changes may require incorporating modification kits or replacement with latest hardware models.

The requirement for refurbishment imposes design requirements for ease of maintenance. For the APS, this seems to establish a need for designing major subsystems into modules that are removed as a unit from the vehicle. The external location of the thruster modules makes it practical to design the interface between the module and the vehicle so that it can be easily broken. Within each module it is necessary that components with high failure rates be designed for ease of replacement.

The requirement for reuse, however, has probably an even greater impact than the refurbishment requirement on the system and component design. The impact is, however, more subtle. After vehicle refurbishment it is necessary to determine the relative reliability for the next flight. This poses the questions of the detail of checkout required, the amount of instrumentation required, the reliability of the instrumentation, and the degree of conservatism to be employed in the component design.

A tentative instrumentation list is given in Appendix I. The function of the APS instrumentation is to provide information for redundancy switching, trend analysis data, and ground checkout measurements as needed to perform routine maintenance and pre-flight checkouts.

This conservatism, or reliability for reuse factor, is also dependent upon the seriousness of a malfunction of the component considered. When redundancy is used, there may be a possibility of allowing some degradation of individual components. The use of redundancy, however, increases the basic hardware cost of the vehicle and increases the hardware replacement frequency.

The question of hardware development and qualification cost must also be related to the refurbishment and reuse requirements. Is it more expensive to develop a component for reuse and refurbishment, or is it more expensive to develop a component that only operates for a single mission?

With a completely reusable system it may be possible to conduct full scale tests in orbit and save some of the development and qualification costs associated with ground tests in a simulated space environment.

Table IV-9 gives a tentative schedule of the frequency at which the various levels of maintenance are performed. An engineering inspection is scheduled after the very first flight. An engineering inspection involves a tear down of the system into its major components for detailed inspection. This is deemed necessary at this time due to the ground testing environment and the flight environment. The first major overhaul (replace/refurbish cycle) of the system is scheduled after the 5th flight. The time between engineering inspections and between overhauls increases during the flight operations until in the OC portion of the program, when only one engineering inspection is performed between major overhauls, which occurs every 20th flight.

The maintenance crew required for auxiliary propulsion system maintenance is composed of the following personnel:

Engineers	-	2
Inspectors	-	2
Technicians	-	8
Analysts	-	3
		15

Table IV-9. Scheduled Maintenance Frequency
Auxiliary Propulsion System

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational > 20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	1, 3	5, 15	10
Replace/ Refurbish	5	10, 20	20

* No. of flight after which the maintenance level is performed.

A discussion of the tasks involved in the various levels of maintenance is presented below. A more detailed breakdown of the time involved in performing the various tasks is presented in Appendix I.

Routine Inspection

The routine inspection is performed after every mission and includes a review of the flight data, various functional tests, proof pressure, calibration, etc. The flight data review is expected to "flag-out" major malfunctions that occur during flight. Also, components that have exceeded duration or duty cycle limitations will be indicated. After these components are tagged for replacement, there is the large question of determining whether the remaining equipment is flight-worthy. The question revolves around such considerations as whether component operation is marginal, whether failure is imminent, or whether operation is outside of specified tolerance. For instance, if a thruster fails to operate, this is a clear case of failure which the flight data can "flag-out" without appreciable difficulty. The "gray" areas occur when the thruster has an intermittent malfunction, such as: missing a single pulse for some unknown reason; off-mixture ratio operation due to partial system plugging; off-thrust operation; low specific impulse; propellant leakage; reduced valve response times for opening or closing; igniter spark plug misfiring; thermal control degradation; etc. The flight data analyses may be able to distinguish some of the "gray" areas of performance shortcomings, but certainly not all of them. For this reason it is assumed that a functional checkout of the APS will occur at the vehicle level prior to initiation of maintenance.

The functional checkouts that are performed as part of the routine inspection will be highly automated and include such functions as:

1. Electrical continuity of cables, controls, valves, heaters, and transducers.
2. Leak checks at operational pressures.

3. Functional check of calibration of transducers, pressure switches, thermostats, relief valves, etc.

4. Gas flow checks of systems to verify pressure drops.

5. Sequencing tests of valves, igniters and other controls.

The routine inspection has been estimated to require 240 manhours to complete.

Engineering Inspection

Engineering inspection of the APS in the vehicle operational phase (OC) is assumed to occur every 10 flights.

Every thruster module will be removed from the vehicle and subjected to highly automated bench tests. The functionals will consist of gas flow checks of instrumentation calibrations, valve functionals, igniter electrical tests, and continuity and resistance checks of electrical cables and components.

Engineering inspection of the propellant accumulators will be essentially the same as routine inspection. The accumulators will be designed to operate at pressures on the order of 6.9×10^6 N/m^2 (1000 psia) and, with an adequate design safety factor, should exceed the life capability of the vehicle (over 100 flights). It is assumed that the accumulators remain installed for the life of the spacecraft and that they can be subjected to inspection, proof pressure, and leak tests without removal.

The propellant conditioning and propellant storage modules are much more difficult to remove and replace because they are internal to the vehicle and require a much more complex interface with the vehicle and other subsystems. The propellant conditioning modules will require less frequent maintenance because they are subject to fewer operational cycles. The propellant conditioning modules will probably function only 20 times per flight at a maximum. Inspection of the propellant conditioning modules will be difficult. Methods of detecting bearing wear and seal leakage must be

perfected. The heat exchangers will probably be replaced on the basis of the number of thermal cycles imposed since it will not be possible to detect incipient failure due to structure fatigue. The life capability will, of course, be a function of the amount of conservatism in the design, but arbitrary removal and inspection every 10 flights is a reasonable design goal.

It will probably be convenient to disassemble the propellant conditioning modules to the level of major subassemblies prior to checkout. This would not have a major impact on refurbishment costs, since it is estimated that these modules will only be removed from the spacecraft every 10 flights.

The turbopumps would be given spin and balance tests in addition to flow, leakage, electrical, instrument calibration, etc. Liquid nitrogen pumping tests may be required.

The heat exchangers would be subjected to pressure, flow, and leakage tests.

The gas generator subassemblies would be given the same functionals as the thrust chamber modules and may use the same test equipment.

The control modules will be removed and inspected. Bench testing of the control units will consist of gas flow tests, leak tests, functionals, calibration of transducers, pressure tests, calibration of pressure regulation and relief valve settings, etc.

After the engineering inspection tasks are completed, the routine inspection tasks are performed. The total manhours estimated for engineering inspection including the routine maintenance functions is 1110 manhours. The cost of the hardware replaced during this maintenance level is estimated to be 1 percent of the unit cost, i.e., $23,600. This hardware consists of thruster igniters, propellant filters, intercomponent seal, etc.

Replace/Refurbish

The replace/refurbish maintenance level is performed every 20th flight in the operational phase (OC). This maintenance level involves

removing the auxiliary propulsion system from the vehicle and replacing it with a refurbished system. The effort required to perform this task has been estimated at 510 manhours.

The actual refurbishment of the system is done at the manufacturer's facility or at a maintenance depot. The cost of this refurbishment has been estimated at 33 percent of the unit cost, i.e., $772,000. Table IV-10 indicates a breakdown of the system into major components with assumed decisions relative to disposition of removed components. The decisions are based on an assumption that each component has flown 20 missions over a nominal two-year time period. The actual life of a component before refurbishment may include one or two years of shelf life in addition to an operational life that exceeds the nominal two years. It seems reasonable to expect five years may intervene between the date of original manufacture of a component until refurbishment. This type of calendar life has a distinct influence on the hardware disposition decisions, especially for components that are highly stressed or that contain plastic or elastomer parts.

Table IV-11 summarizes the refurbishment costs. The components that can be used without refurbishment are found to be components that are relatively inexpensive such as structural mounts and propellant tanks. The components and materials that are discarded are also relatively inexpensive parts such as igniters, wiring, and insulation. The components that are repairable are relatively complex, requiring a relatively large amount of labor, such as for propellant valves. One of the largest expenses, however, results simply from the cost of disassembly, reassembly, and acceptance testing at the module level of assembly.

Electrical Power

As mentioned previously, the fuel cell data is based on a fuel cell technology program being conducted by NASA. For purposes of this study, a 2000 hour capability (10 missions) was assumed between major overhauls. The major overhaul or refurbishment is assumed to cost 25 percent of the unit cost.

Table IV-10. Disposition of APS Refurbishment Hardware

	No. Per Module	Replace	Repair and Reuse	Reuse As Is	Purchase Cost x $1,000		Refurbishment Cost x $1,000	
					Per Unit	Per Module	Per Unit	Per Module
Thruster Module								
Mount	1			X	4	4	0	0
Electrical Harness	1	X			2	2	2	2
Insulation	1	X			2	2	2	2
Tubing & Manifold	1		X		2	2	0	0
Thrust Chamber Assembly								
Hydrogen Valve	5		X		20	100	5	25
Oxygen Valve	5		X		20	100	5	25
Igniter	5				2	10	2	10
Injector	5	X	X		12	60	2	10
Thrust Chamber	5		X		12	60	2	10
Pressure Transducer	5		X		2	10	1	5
Module Assy & Test	1					50		30
Total						400		115

Table IV-10. Disposition of APS Refurbishment Hardware
(continued)

	No. Per Module	Replace	Repair and Reuse	Reuse As Is	Purchase Cost x $1,000		Refurbishment Cost x $1,000	
					Per Unit	Per Module	Per Unit	Per Module
Accumulator Modules								
Hydrogen Accumulator	1			X	20	20	0	0
Oxygen Accumulator	1			X	20	20	0	0
Total						40		
Controls Module								
Relief Valves	4		X		1	4	Nil	Nil
Check Valves	4		X		Nil	Nil	Nil	Nil
Pressure Transducers	4		X		1	4	Nil	Nil
Valves - Line Pressurization	4		X		7	28	2	8
Valves Main Tank Pressurization	4		X		7	28	2	8
Bleed	4		X		7	28	2	8
Pressure Switches - Line	4		X		1	4	Nil	Nil
Accumulator	4		X		1	4	Nil	Nil
Module Assy & Test						20		20
Total						120		44

Table IV-10. Disposition of APS Refurbishment Hardware (continued)

	Module	Replace	Repair and Reuse	Reuse As Is	Purchase Cost x $1,000		Refurbishment Cost x $1,000	
					Per Unit	Per Module	Per Unit	Per Module
<u>Propellant Conditioning Module</u>								
Electrical Harness	1	X			2	2	2	2
Tubing & Manifold	1		X		2	2	1	1
Insulation	1	X			1	1	1	1
Pump	1		X		15	15	3	3
Turbine	1		X		15	15	3	3
Heat Exchange	1		X		8	8	2	2
GG Hydrogen Valve	1		X		8	8	2	2
GG Oxygen Valve	1		X		8	8	2	2
GG Injector	1		X		5	5	1	1
GG Chamber	1			X	5	5	0	0
GG Igniter	1	X			2	2	2	2
Thermistors	5	X			1	5	1	5
Thermostats	2	X			1	2	1	2
Pressure Transducer	5	X			1	5	0	0
Module Assy & Test						40		30
Total						120		56

Table IV-11. Summary of APS Refurbishment Costs

Type of Module	No. Per Vehicle	Replacement Cost x $1,000		Refurbishment Cost x $1,000		
		Per Module	Per Vehicle	Per Module	Per Vehicle	% of Replacement Cost
Thruster	4	400	1600	115	460	28.7
Propellant Conditioning	4	120	480	56	224	46.7
Accumulator	2	20	40	0	0	0
Controls	2	120	240	44	88	36.7
Total			2360		772	32.7

Table IV-12 presents the current estimate of the frequency at which the various levels of maintenance are performed. During the flight test program, the system is torn down for an engineering inspection three times and completely refurbished twice. This is done to determine the reusability of the system and to develop the capability to extend the life to 2000 hours.

The maintenance crew for the electrical power system is made up of the following:

Engineers	-	1
Inspector	-	0.5
Technicians	-	3
		3.5

The tests involved in the various levels of maintenance are described below.

Routine Inspection

This will be performed after every flight and consists of: (1) a visual inspection of the electrodes for evidence of excessive carbonate buildup, and (2) performing an automated electrical test wherein voltage and current outputs are monitored under various load conditions. The electrical test would be commanded by the on-board computer and the test data would be telemetered to a data reduction center for analysis. It is estimated that it will take 28 manhours to complete this inspection.

Engineering Inspection

At key milestones during flight test and the initial operational phase of the program, the fuel cells will be removed from the vehicle and subjected to an extensive visual inspection and checkout on a unit level tester. After the system has been reinstalled, a routine inspection will be performed. It is estimated that it will require 196 manhours to accomplish this task. The hardware replaced (filters, seals, etc.) is estimated to cost approximately 5 percent of the unit cost.

Table IV-12. Scheduled Maintenance Frequency
Electrical Power System

Maintenance Level	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	-	Every Flight	Every Flight
Engineering Inspection	2, 3, 4	5	-
Replace/ Refurbish	1, 5	10, 20	10, 20

* No. of flight after which the maintenance level is performed.

Replace/Refurbish

At the end of the expected life of the system, the system will be removed and replaced with a refurbished system. It is estimated that 56 manhours will be required to remove, replace, and perform a routine inspection. It is assumed that the system will be refurbished at the manufacturer or a refurbishment depot at a cost of 25 percent of the unit cost.

Avionics

Avionics system maintenance has been planned to include routine inspections, engineering inspections, and replace/refurbish operations. This planning is based on the subsystem characteristics defined previously. A typical unit refurbishment operation will involve the following steps:

1. Factory unit level checkout test
2. Remove cover and visually inspect
3. Perform module checkout tests to locate faulty module
4. Either repair faulty module or install new one
5. Perform necessary visual inspections
6. Perform sub-tier electrical checkout tests
7. Perform acceptance tests which will probably include vibration and temperature

With the built-in test equipment (BITE) and computerized diagnosis capability on-board, it is estimated that any failed black box will always be identified without resort to extensive external AGE. The replacement of a failed unit with a known good unit from the bonded storeroom is expected to take 8 manhours and can be accomplished by the normal maintenance crew. After installation of a new unit, it is estimated that complete avionic system integrity can be established by means of the on-board computerized self-test capability within one hour. Another three hours should be allowed for scrutiny of the telemetered results of all diagnostic tests.

Table IV-13 shows the scheduled maintenance frequency for the various levels of maintenance. During the flight test program, the avionics system is removed for detailed inspection, testing and calibration after the first and second flights. After the 5th flight, the system is removed and refurbished. For the initial operation phase (IOC), the system is removed for detailed inspection after the 10th and 20th flight. No scheduled refurbishment occurs. For the operational phase, only routine maintenance is performed. Therefore, for the avionics system no scheduled replacement of hardware occurs during any of the operational phases (IOC and OC). Repair and replacement is "on condition."

The maintenance crew for the avionics crew is made up of the following people:

Engineers	-	2
Inspectors	-	2
Technicians	-	8
		12

Routine Inspection

This will be performed after each flight and will consist of reviewing the flight data, visual inspection of electrical cables and connectors, and running the onboard COFI routines which exercise BITE in the subsystems. In addition, the MICRON IMU will be removed every fifth flight for recalibration. The manpower estimate for routine inspection is 168 manhours.

Engineering Inspection

At key points in the flight program, the avionics system will be removed from the vehicle and each unit checked out on a unit level tester. The system will then be reinstalled on the vehicle and a routine inspection performed. The manpower estimate for this task is 1068 manhours.

Table IV-13. Scheduled Maintenance Frequency

Avionics

Maintenance	Phase I Flight Test 1st 5 Flights	Phase II (IOC) Initial Operation, Next 20	Phase III (OC) Operational >20
	*	*	*
Routine Inspection	Every Flight	Every Flight	Every Flight
Engineering Inspection	1, 2	10, 20	-
Replace/ Refurbish	5	-	-

* No. of flight after which the maintenance level is performed.

Replace/Refurbish

To remove and replace the avionics system in the vehicle and then perform a routine inspection requires approximately 456 manhours. The refurbishment or repair of the avionics system has been estimated at 15 percent of the unit cost on the average.

Vehicle Level Testing

Each component and module should be designed to facilitate testing, as well as replacement, and specific requirements should be included in the original instructions to the design engineers. The BITE concept should be used wherever feasible and should incorporate automatic switching to redundant units and visual indicators for failed conditions.

It is anticipated the Shuttle system will employ an automated approach to testing based on a standardized set of test equipments (e.g., the Unified Test Equipment, UTE concept). The Tug can use the same control, monitor, display, recording and computation units with appropriate software, and much of the same stimulation provisions should be applicable. Full compatibility with the Shuttle equipment will permit the sharing of units and the integration of Tug (and payload) flight readiness testing with Shuttle testing following loading.

Lower level testing, as during component replacement, may involve a limited array of manual test gear, but these should also be subject to elimination as the automated system matures and advantage can be taken of its centralized control and computational capability through specialized software and appropriate interface units.

Pre-Maintenance Test

Following delivery to the maintenance area, an integrated systems test will be performed on the Tug. The test results will be analyzed in conjunction with prior testing results, telemetered data received during flight crew squawks, and data recorded on-board. Out-of-tolerance, failed

or suspect components will be identified and the required maintenance action scheduled accordingly. Other components with built-in test equipment (BITE) will also indicate required replacement by their automatically triggered indicators (red flags, or lights, etc).

The design of the test procedure will be specifically tailored to each processing of a Tug. Generally, the tests will be end-to-end testing of functional strings with "signatures" or deductive logic used to pin-point failures at the LRU level. More detailed testing will be added as warranted by trend data from previous testing, by other Tug vehicle test experience and as indicated from the flight crew's comments and analysis of the TLM and OBC data. All testing will be automated using standardized routines, but with the provision for manual override for specific checks.

The test should be relatively brief and will involve:

Test Duration	-	12 Hours
Crew Size	-	25
Man-Hours	-	300
Projection for Mature System	-	150

Post-Maintenance Test

This test phase follows the maintenance activity and verifies that the vehicle is flight-ready. It will involve a thorough systems level testing of all subsystems including redundant switching. The early operational phase may include testing to the LRU level in certain critical cases. Later in the operational phase, as the hardware matures and confidence is built up, testing can be progressively reduced in complexity and only abbreviated integrated system tests will be required.

The post-maintenance testing will be a complete functional check of all subsystems and will involve the following:

Test Duration	-	32 Hours
Crew Size	-	25
Man-Hours	-	800 Hours
Projection for Mature System	-	600 Hours

E. SCHEDULED MAINTENANCE COSTS

The tabulation of the costs associated with scheduled maintenance of the eleven major vehicle areas as described in the previous sections is contained in this section. Using the data generated in the previous two sections and in Appendix I, Tables IV-14 and IV-15 were generated. Table IV-14 is a summary of the scheduled maintenance frequencies of all the vehicle areas. Table IV-15 is a tabulation of all the costs for Phase II (IOC) and Phase III (OC) of the flight program. Costs were not tabulated for the Flight Test Phase. Maintenance frequencies for this phase were only estimated to allow a basis for Phase II and III. The numbers in Table IV-14 represent the number of the flight after which a particular level of maintenance is performed.

The numbers in Table IV-15 apply to Phase II which is the IOC portion of the program and to Phase III which is the OC portion of the program. The numbers to the left of the slash refer to IOC and those to the right refer to OC. Where there is no slash, the number applies to both phases. The numbers are based on 20 flights per phase. The OC maintenance costs repeat every 20 flights.

The first column in Table IV-15 lists the major vehicle areas that were described in a previous section. The second column is the estimated cost of the item. The next 3 major columns are the 3 maintenance levels, routine inspection, engineering inspection, and replace/refurbish. Under each of these 3 major columns are 3 subcolumns, the first of which lists the number of times during 20 flights that that particular level of maintenance is performed. The second subcolumn lists the number of manhours required to perform that particular level of maintenance one time, and the final subcolumn is the total manhours required to perform that level of maintenance in 20 flights.

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Table IV-14. Scheduled Maintenance Frequency

ITEM	PHASE I FLIGHT TEST 1st 5 FLIGHTS			PHASE II (IOC) INITIAL OPERATION, NEXT 20			PHASE III (OC) OPERATIONAL, >20		
	ROUTINE INSPECT.	ENG. INSPECT.	REPLACE REFURB.	ROUTINE INSPECT	ENG. INSPECT.	REPLACE REFURB.	ROUTINE INSPECT.	ENG. INSPECT.	REPLACE REFURB.
BASIC STRUCTURE	ALL	1, 3	5	ALL	3, 6, 15	10, 20	ALL	5, 15	10, 20
METEOROID SHIELD	"	-	5 (50%)	"	-	10, 20	"	-	10, 20
TUG TO P/L DOCK.	"	-	5	"	-	10, 20	"	-	10, 20
TUG TO SHUTTLE DOCK.	"	-	5	"	-	10, 20	"	-	10, 20
PROP. TANKS	"	-	5	"	-	20	"	-	20
INTERFACE PANEL	"	1, 3	5	"	5, 15	10, 20	"	-	10, 20
TANK INSULATION	"	1, 3	5	"	3, 6, 15	10, 20	"	5, 10, 15	20
MAIN PROPULSION	"	1, 3		"	7, 13	2, 20	"	10	20
AUX. PROPULSION	"	1, 3	5	"	5, 15	10, 20	"	10	20
ELECTRICAL POWER	-	2, 3, 4	1, 5	"	5	10, 20	"	-	10, 20
AVIONICS	"	1, 2	5	"	10, 20	-	"	-	-

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Table IV-15. Scheduled Maintenance Costs IOC/OC *, 20 Missions per Phase

ITEM	UNIT COST K $	ROUTINE INSPECTION			ENGINEERING INSPECTION			REPLACE/REFURBISH			MANPOWER COSTS		HARD-WARE COSTS K $	TOTAL SCHED-ULED COSTS K $
		Freq.	Man-Hrs.	Sub. Man-Hrs.	Freq.	Man-Hrs.	Sub. Man-Hrs.	Freq.	Man-Hrs.	Sub. Man-Hrs.	Total Man-Hrs.	Cost K $		
		*		*	*		*	*		*	*	*	*	*
BASIC STRUCTURE	-	15/16	24	360/384	3/2	48	144/96	2	72	144	648/624	11	0	11
METEOROID SHIELD	100	18	60	1080	0	-	0	2	60	120	1200	20	200	220
TUG-P/L DOCK.	200	18	24	432	0	-	0	2	48	96	528	9	100	109
TUG-SHUTTLE DOCK.	100	18	24	432	0	-	0	2	48	96	528	9	50	59
PROPEL. TANKS	250	19	128	2432	0	-	0	1	1100	1100	3532	60	250	310
INTERFACE PANELS	100	16/18	12	192/216	2/0	36	72/0	2	36	72	336/288	6/5	220/200	226/205
TANK INSULATION	300	15/16	64	960/1024	3	682	2046	2/1	776	1552/776	4558/3846	77/65	1215/900	1292/965
MAIN PROPULSION	1030	16/18	189	3024/3402	2/1	441	882/441	2/1	621	1242/621	5148/4464	88/76	642/321	730/397
AUX. PROPULSION	2360	16/18	240	3840/4320	2/1	1110	2220/1110	2/1	510	1020/510	7080/5940	120/101	1592/796	1712/897
ELEC. POWER	1070	17/18	28	476/504	1/0	196	196/0	2	56	112	784/616	13/10	590/536	603/546
AVIONICS	3530	18/20	168	3024/3360	2/0	1068	2136/0	0	456	0	5160/3360	88/57	0	88/57
SYSTEM EFFORT														
PRE-MAINT. TEST		20	300/150	6000/3000							6000/3000	102/51		102/51
POST-MAINT. TEST		20	800/600	16000/12000							16000/12000	272/204		272/204
												875/678	4859/3353	5734/4031
									COST PER MISSION K $		=	44/34	243/168	287/202

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The next major column in Table IV-15 is the manpower costs. The first subcolumn under manpower costs is the total manhours required to perform maintenance for a particular major vehicle area over 20 flights. The next subcolumn is the total manpower costs. This was calculated assuming an average cost of $17 per hour for the maintenance crew. Table IV-16 shows the derivation of the average crew cost based on industry averages and the specific crew mix indicated. The average cost indicated in Table IV-16 was rounded up to $17 per hour for all manpower costing in this study.

The next major column after manpower costs is hardware costs. This is the cost of hardware replaced during the performance of all scheduled maintenance levels. For the propellant tank insulation system, this column also includes the cost of the vacuum test that is performed during engineering inspection and replace/refurbish maintenance cycles.

The last major column is the summation of the manpower costs and the hardware costs. Along the bottom of Table IV-15 are listed the costs associated with system level effort, i.e., pre-maintenance and post-maintenance testing. These costs are then summed to obtain the total scheduled maintenance costs for a 20-flight IOC and OC operation. Also shown in Table IV-15 is the cost per flight for scheduled maintenance, i.e., $287,000 for IOC and $202,000 for OC.

F. UNSCHEDULED MAINTENANCE COSTS

The maintenance costs presented in the previous section were strictly for scheduled maintenance. The costs associated with random failures are presented below.

The mean time between failures (MTBFS) for the avionics system are as noted in the previous section and in Appendix I. The MTBF figures listed for each avionics unit are the values expected to be achieved at maturity of the equipment. Experience with avionic equipment indicates that the mature MTBF (theoretical MTBF) is achieved only after the complete R&D phase

Table IV-16. Estimate of Direct Labor Costs

BASELINE VALUES				OOS AUX. PROP. MAINT. CREW		
TYPE OF LABOR	$/HR. (1) 1971	BURDEN (2) %	TOTAL $/HR 1971	CREW MEMBERS	MAINTENANCE CREW SKILLS FACTORS	TOTAL $/HR. 1971
Engineer	8.00	175	22.00	2	1.0	44.00
Inspector	4.36 AVERAGE	200	13.00	2	1.2	31.20
Technician		200	13.00	8	1.2	124.80
Analysts		200	13.00	3	1.2	46.80
			TOTALS	15		246.80
					AVERAGE	16.45

(1) (a) Engineering rates obtained from 1968 survey of contractors by Los Alamos Scientific Lab.

(b) Manufacturing rates obtained from 1971 average earnings of aircraft production workers.

(2) Estimated from one contractor's project records (1967)

(a) Engineering labor @ direct rate of $6.00/hr; total burdened @ $16.33/hr.

(b) Manufacturing labor @ direct rate of $4.14/hr; total burdened @ $12.50/hr.

(c) Total burden includes all overhead, travel, computer rental, G&A, material handling and overtime premium but does not include fee.

and early flight test phase of any program have been completed. In order to account for this effect, maintenance costs associated with random failures for the mature vehicle, OC phase, are doubled to obtain the costs for the IOC phase of the program. Since no failure rate information was available for the mechanical systems, the average MTBF for mechanical systems per unit cost was assumed to be 20 percent of the average electrical failure rate per unit cost.

The maximum length mission for the Tug is expected to be 6 days or 144 hours. For this analysis, to account for environmental stress factors and ground test time, an equivalent time of 200 hours per flight was assumed. All redundant equipment was assumed to be active for 200 hours except the auxiliary propulsion system and the laser radar. Only 50 percent of the auxiliary propulsion system was assumed to be operating for the full 200 hour mission. Estimates of the operating time of the laser radar have ranged from 15 to 50 hours. For this study, one laser radar was assumed to be operating 50 percent of the time for a 200 hour mission.

Built-in test equipment (BITE) failure rate was assumed to be 10 percent of the total system. Twenty-five percent was added to all failure rate costs to account for false alarms, etc. The component refurbishment cost is assumed to be a percentage of the unit cost. The same refurbishment cost factor that was used for scheduled maintenance was applied to the random failure estimate except for the auxiliary propulsion system. This was reduced from 33 percent for scheduled refurbishment to 10 percent for random failures due to the types of failures anticipated, e.g., valve leakage, igniter failure, etc.

The ratio of people costs, exclusive of that associated with system level testing, to hardware costs for scheduled maintenance was approximately 13 percent. Therefore, 13 percent was added to the hardware costs for random failures to account for labor costs.

The equation used to calculate random failure costs is given below:

$$C = \frac{T}{MTBF} \times UC \times RC \times N$$

where

C = cost per flight

T = flight time (200 hours)

$MTBF$ = mean time between failure

UC = cost of unit

RC = refurbishment cost factor

N = number of units in the system

Due to the uncertainty in the capability of the propellant tanks to complete their expected design life of 20 flights before leaking, a mean time between leakage was assumed that necessitated the removal of the propellant tank once every 20 missions as a result of leakage in addition to the scheduled tank replacement due to life limitations. This is paramount from a costing viewpoint to having a tank design with a 10 mission life capability.

The costs associated with random failure, unscheduled maintenance, are tabulated in Table IV-17 for IOC and OC. The costs listed are for a total of 20 missions per flight phase. The total cost per mission for IOC and OC is also shown in Table IV-17. No random failures of the basic structure or the meteoriod shield were considered.

G. TOTAL TUG REFURBISHMENT COSTS

The previous sections have discussed separately the costs associated with scheduled maintenance and unscheduled maintenance or random failures. This section of the report ties together these groups of costs and makes some observations concerning the relative magnitude of the predicted cost numbers. Table IV-18 presents the refurbishment costs on a per mission basis for both scheduled and unscheduled maintenance for the IOC and OC

Table IV-17. Tug Refurbishment Costs - 20 Missions Per Phase

Unscheduled Maintenance

Thousands of Dollars

	PHASE II (IOC)			PHASE III (OC)		
	Labor	Hardware	Total	Labor	Hardware	Total
Basic Structure	-	-	-	-	-	-
Meteoroid Shield	-	-	-	-	-	-
Tug-P/L Dock.	3	22	25	2	11	13
Tug-Shuttle Dock.	-	6	6	-	3	3
Propel. Tanks	70	500	570	35	250	285
Interface Panels	-	4	4	-	2	2
Tank Insulation	8	64	72	4	32	36
Main Prop.	80	610	690	40	305	345
Aux. Prop.	80	620	700	40	310	350
Elect. Power	10	80	90	5	40	45
Avionics	80	604	684	40	302	342
TOTAL	331	2510	2841	166	1255	1421
Cost Per Mission	17	125	142	8	63	71

Table IV-18. Tug Refurbishment Cost Per Mission
Thousands of Dollars

	PHASE II - IOC			PHASE III - OC		
	Scheduled	Unscheduled	Total	Scheduled	Unscheduled	Total
Basic Structure	0.6	0	0.6	0.6	0	0.6
Meteoroid Shield	11.0	0	11.0	11.0	0	11.0
Tug-P/L Dock.	5.4	1.3	6.7	5.4	0.6	6.0
Tug-Shuttle Dock.	2.9	0.3	3.2	2.9	0.1	3.0
Propel. Tanks	15.5	28.5	44.0	15.5	14.3	29.8
Interface Panels	11.3	0.2	11.5	10.3	0.1	10.4
Tank Insulation	64.6	3.6	68.2	48.3	1.8	50.1
Main Prop.	36.5	34.5	71.0	19.8	17.3	37.1
Aux. Prop.	85.6	35.0	120.6	44.9	17.5	62.4
Elect. Power	30.2	4.5	34.7	27.3	2.2	29.5
Avionics	4.4	34.2	38.6	2.9	17.1	20.0
System Tests	18.7	0	18.7	12.7	0	12.7
TOTAL	286.7	142.1	428.8	201.6	71.0	272.6

flight phases. The total cost is \$429,000 per flight during IOC and \$273,000 per flight during OC. This represents a reduction of approximately 1/3 on the maintenance costs from IOC to OC. This is due to the reduction in the number of scheduled replacements and engineering inspections during OC. In addition, the unscheduled maintenance costs in the OC phase represent a mature system whereas, in the IOC phase of the program, the mean time between failures (MTBFs) of the various systems were assumed to be only half of their mature values.

The unscheduled maintenance costs are about 1/3 of the total maintenance costs for IOC and about 1/4 of the total costs for OC. This general trend for the total vehicle is reversed for the avionics system, i.e., the unscheduled maintenance costs for the avionics system are approximately 8 times higher than the scheduled maintenance during IOC and approximately 6 times higher during OC. This is due to the philosophy of "on condition" maintenance for the avionics system, i.e., maintenance is performed only after a failure occurs. This philosophy is possible for the avionics system because the system is redundant and it essentially never wears out. This type of philosophy is not feasible for a system like the propellant tank insulation system or the main propulsion system where there are definite wearout modes and the systems are not redundant.

Table IV-19 presents the refurbishment costs for IOC and OC as a percentage of the vehicle first unit production cost. The cost of the vehicle was assumed to be 10.97 million as noted in Table IV-19. The avionics, electrical power, and propulsion systems costs are the same costs that were used for those particular systems in this study. The costs for structure and integration, assembly, checkout and test were obtained from cost estimating relationships (CERs).

The cost for IOC is 3.91 percent and 2.49 percent for OC. These percentages are made up of five main drivers. For OC, these are in order of importance: (1) the auxiliary propulsion system; (2) the propellant tank insulation system; (3) the main propulsion system; (4) the propellant tanks,

Table IV-19. Tug Refurbishment Costs - Percent Per Flight *

	IOC	OC
Basic Structure	0.01	0.01
Meteoroid Shield	0.10	0.10
Tug-P/L Dock.	0.06	0.05
Tug-Shuttle Dock.	0.03	0.03
Propel. Tanks	0.40	0.27
Interface Panels	0.10	0.09
Tank Insulation	0.62	0.46
Main Prop.	0.65	0.34
Aux. Prop.	1.10	0.57
Elect. Power	0.32	0.27
Avionics	0.35	0.18
System Tests	0.17	0.12
TOTAL	3.91	2.49

* Percent of vehicle first unit production cost per flight.

First Unit Hardware Cost

	$ Millions
Structure	2.02
Avionics	3.53
Elect. Power	1.07
Propulsion	3.39
Integration, Assembly, Checkout and Test	0.96
	10.97

and (5) the electrical power system. In the IOC phase the avionics system is more expensive to maintain than the electrical power system. This is a result of the fact that almost all the cost of maintaining the avionics system is due to unscheduled maintenance and the relative immaturity of the system in the IOC phase of the program. The major cost of maintaining the electrical power system is for scheduled maintenance which is about the same for both flight phases.

APPENDIX A. SUMMARY REFURBISHMENT DATA AND OPERATIONS SHEETS

For purposes of this study, the Tug vehicle was divided into eleven major vehicle areas:

1. Basic Structure
2. Meteoroid Shield
3. Tug/Payload Docking Mechanism
4. Tug/Shuttle Docking Mechanism
5. Interface Panels
6. Propellant Tanks
7. Propellant Tank Insulation System
8. Main Propulsion System
9. Auxiliary Propulsion System
10. Electrical Power
11. Avionics

Basic data that would be pertinent to this study were generated for each of the major vehicle areas. These data were then tabulated on what is referred to as "Refurbishment Data Sheets" and "Refurbishment Operations Sheets." These sheets are contained in this appendix. A narrative discussion is presented in Section IV C. and IV D. of the body of this report.

A. REFURBISHMENT DATA SHEETS

The "data sheets" contain all of the pertinent descriptive information concerning each of the major vehicle areas, viz., the function of the equipment, some physical characteristics such as weight and size, an estimate of the unit cost and maturity of the equipment, expected failure modes and rates where known, an estimate of the cost to refurbish the equipment, and a tentative instrumentation list which depicts some of the flight data to be analyzed and test points for ground checkout during maintenance.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Basic Structure

Function - To provide structural integrity to the vehicle and to react main engine thrust loads.

Characteristics

Weight - 155 kg (342 lb)
Size - 4.57 m x 9.14 m (15' x 30')
Maturity - Current technology

Failure Modes and Effects

Random

Over stress failure due to overloading.

Average Unit Refurbishment Cost

100% of unit cost if failed.

Test Points

None

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Meteoroid Shield

Page 1 of 1

Function - Provide vehicle with meteoroid protection during exposure to space environment.

Characteristics

Weight	-	127 kg (280 lb)
Size	-	4.57 m x 6.10 m (15' x 20')
Unit Cost	-	$100,000
Maturity	-	Current technology

Failure Modes and Effects

Random

Meteoroid penetration. Depending on the size of the meteoroid, the structural integrity of the insulation and propellant tanks could be compromised if the shield were penetrated. In addition, any system would be subject to damage in the advent of a meteoroid penetration.

Wearout

Replaced after 10 missions due to excessive handling, e.g., the shield is removed after every flight to allow inspection of the tank insulation.

Average Refurbishment Cost

Negligible

Test Points

None

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Tug to Payload Docking Mechanism

Function - Provides mechanism to deploy, retrieve and secure payload to Tug.

Characteristics

Weight	-	68 kg (150 lb)
Size	-	4.57 m x 0.467 m (15' x 1.5')
Unit Cost	-	$200,000
Maturity	-	Current technology
Description	-	Consists of latches, shock absorbers, and supporting structure.

Failure Modes and Effects

Random

1. Solenoid malfunction results in the failure of the latching mechanism to function. This would result in the inability of the Tug to release or secure a payload.
2. A malfunction of the shock absorbers could cause a hard docking which may result in structural damage of the docking mechanism or the payload.

Average Unit Refurbishment Cost

The average unit refurbishment cost is expected to be 25% of the unit cost, viz., $50,000 every 10 missions.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Tug to Payload Docking Mechanism

Test Points

Measurement	No.	In-Flight	Ground Checkout
Helium Pressure	1	X	X
Hydraulic Pressure	1	X	X
Mechanical Latch Position	4	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Tug to Shuttle Docking Mechanism

Function - Provide mechanism to deploy, retrieve, and secure Tug to Shuttle.

Characteristics

Weight	-	164 kg (665 lb)
Size	-	3.3 m x 2.4 m (13' x 9.5')
Unit Cost	-	$100,000
Maturity	-	Current technology
Description	-	Consists of latches, shock absorbers, thrust equalizing support pads, and supporting structure.

Failure Modes and Effects

Random

1. Solenoid malfunction results in the failure of the latching mechanism to function. This would result in the inability of Shuttle to deploy or retrieve the Tug.
2. A malfunction of the shock absorbers could cause a hard docking which may result in structural damage to the docking mechanism or the Tug.

Average Unit Refurbishment Cost

The average unit refurbishment cost is expected to be 25% of the unit cost, viz., $25,000 every 10 missions.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Tug to Shuttle Docking Mechanism

Page 2 of 2

Test Points

Measurement	No.	In-Flight	Ground Checkout
Mechanical Latches			
Position	12	X	X
Dual Drive Actuator			
Voltage	6	X	X
Base Ring Pivot Actuator			
Position	1	X	
Voltage	1	X	X
Docking Probe			
Position	6	X	
Voltage	3	X	X
Pitch Fitting Latch			
Position	2	X	
Voltage	1	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Interface Panels

Page 1 of 2

Function - To provide electrical and fluid interfaces between the Tug and Shuttle.

Characteristics

Two panels - One for fuel and electrical power and one for oxidizer and electrical signals.

Weight	-	34 kg each (75 lb each)
Size	-	0.46 m x 0.46 m x 0.31 m (1.5' x 1.5' x 1')
Unit Cost	-	$50,000 per panel
Maturity	-	Current technology

Failure Modes and Effects

Random

1. Mismatch of connectors during Tug retrieval is the most probable failure mode. This could result in loss of electrical power, system monitoring and tank insulation purge during reentry.
2. Fluid leaks could occur through the interface connections. This could result in a hazardous condition in the Shuttle bay.

Average Refurbishment Cost

The average refurbishment cost of the interface panel is assumed to be 10% of the unit cost, viz., $5,000 per panel, for the engineering inspection and 100% for replacement.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Interface Panels

Page 2 of 2

Test Points

Measurement	No.	In-Flight	Ground Checkout
All Valves			
Position	12	X	X
Voltage	12	X	X
Umbilical Panel Assembly			
Position	2	X	
Voltage	2	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tanks

Page 1 of 2

Function - Provide storage for liquid O_2 and H_2 propellants.

Characteristics

One H_2 tank

One O_2 tank

Weight	- 323.4 kg (713 lb) H_2 tank
	- 287.1 kg (633 lb) O_2 tank
Size	- 4.42 m x 5.03 m (14.5' x 16.5') H_2 tank
	- 3.81 m x 2.74 m (12.5' x 9') O_2 tank
Unit Cost	- \$150,000 H_2 tank
	- \$100,000 O_2 tank
Maturity	- Requires some technology development to ensure integrity and reusability of thin-walled pressure vessels.

Failure Modes and Effects

Random

1. Inconsistent material properties may result in an excessive amount of leakage during nominal operating pressure conditions.
2. Malfunction of the vent valve could result in an overpressurization of the tank.

Wearout

Propellant tanks are designed for a 20 mission life.

Average Refurbishment Cost

The average refurbishment cost of the propellant tanks is expected to be 100% of the unit cost, viz., \$250,000.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tanks

Test Points

Measurement	No.	In-Flight	Ground Checkout
H_2 Tank			
Temperature	1	X	
Pressure	1	X	
O_2 Tank			
Temperature	1	X	
Pressure	1	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tank Insulation System

SUBSYSTEM: Multilayer Insulation Blankets

Page 1 of 3

Function - Provide thermal protection of the liquid propellant tanks and to maintain each of the propellants (LH_2 and LO_2) at their respective liquid temperatures with acceptable boil-off.

Characteristics

Physical Size:

Hydrogen - 74.3 m^2 (300 ft^2); 30 layers 1.27 cm (0.5 in.) thick

Oxygen - 41.8 m^2 (450 ft^2); 40 layers 1.90 cm (0.75 in.) thick

Weight Per Unit:

Hydrogen - 59 kg (130 lb)

Oxygen - 38.6 kg (85 lb)

Unit Cost - $300,000 (including purge bag and vent valves)

Environmental Limitations:

Maximum Temperature - 478°K (400°F)

Maximum Pressure Difference - 3,447 N/m^2 (0.5 psi), compression

Thermal/Pressure Cycling - TBD

Vibration - TBD

Development Status:

Proposed insulation for this type of application is in the development stage.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tank Insulation System

SUBSYSTEM: Multilayer Insulation Blankets

Page 2 of 3

Failure Modes and Effects

Random

1. Pin and Stud Failure: Separation of insulation from mountings with loss of rigidity and consequent tearing.
2. Butted Joint Failure: Direct thermal short into tank.
3. Surface Delamination: Thermal performance degradation.

Wearout

1. Pin and Stud Failure: Separation of insulation from mountings with loss of rigidity and consequent tearing.
2. Butted Joint Failure: Direct thermal short into tank.

Failure Rates

Wearout

Refurbish every five missions. Total repairable life is 20 missions.

Average Unit Refurbishment Cost

The average refurbishment cost is estimated to be 60% of the unit cost every 5th mission. Every 20th mission the system is replaced with a new unit.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tank Insulation System

SUBSYSTEM: Multilayer Insulation Blankets

Test Points

Measurement	No.	In-Flight	Ground Checkout
Temperature	10 (5 each tank)	X	X (During vacuum test)
Propellant Boiloff	2 (1 each tank)		X (During vacuum test)

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tank Insulation System

SUBSYSTEM: Purge Bag

Page 1 of 2

Function - Provide purge gas enclosure during ground hold, ascent, descent.

Characteristics

Physical Dimensions - 116 m^2 (1250 ft^2), 0.38 cm (150 mils) thick

Weight - 68 kg (150 lb)

Unit Cost - $10,000

Environmental Limitations -

Maximum Temperature - 478°K (400°F)

Maximum Pressure Difference - Difference: 13,789 N/m^2) (2 psi) (compression/tension)

Thermal/Pressure Cycling - $>$1,000 cycles

Vibration - TBD

Development Status - Applicable technology exists.

Failure Modes and Effects

Random

Bag Tear: No gas maintenance (purge) capability; most critical during reentry.

Wearout

Loss of sealing faces: No gas maintenance (purge) capability.

Average Unit Refurbishment Cost

The bag is replaced every 20 missions with a new bag.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tank Insulation System

SUBSYSTEM: Purge Bag

Test Points

Measurement	No.	In-Flight	Ground Checkout
Pressure	5	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Propellant Tank Insulation System

SUBSYSTEM: Vent Valves

Page 1 of 1

Function - Vent insulation purge bag during ground hold, permit insulation venting to space in orbit, and permit insulation back-filling during reentry.

Characteristics

Physical Dimensions	-	0.3 m (1 ft) in diameter
Weight	-	0.9 kg (2 lb) per unit, 4.54 kg (10 lbs) (five units)
Total Cost	-	$12,500
Development Status	-	Current technology

Failure Modes and Effects

Random

Spring Failure: Non-back-filling resulting from non-closing of valves.

Relay Failure: Non-back-filling resulting from non-closing of valves.

Seam Separation: Non-back-filling resulting from non-closing of valves.

Wearout

Valve Seat: Non-back-filling with purge gas.

Seam Wear: Non-back-filling with purge gas.

Failure Rates

Wearout

Replace valves every 20 missions.

Average Unit Refurbishment Cost

The vent valves are replaced every 20 missions with a new unit.

Test Points

None

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Main Engine

Function - The main engine system provides thrust for major velocity changes.

Characteristics

Total Units - 1

Unit Weight - 202 kg (446 lb)

Unit Cost - $950,000

RDT&E Cost - $110 M

Size

Unit Length - 2.08 m (82 in)

Unit Dynamic Diameter - 2.21 m (87 in)

Maturity - Development Required

Failure Modes and Effects

Wearout

1. Thrust chamber burnout. This failure is due to thermal fatigue and results in minor changes in engine performance and thrust.

2. Thermal fatigue failures in the turbine. The failure is characterized by loss of turbine blades and decreased engine thrust level.

Failure Rates

Wearout

Engine designed for 10 hour operation, 300 starts (20 missions).

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Main Engine

Average Unit Refurbishment Cost

An engineering inspection is performed after 5 hours of operation at a cost of 6% of a new system. The system is completely refurbished after 10 hours operation at a cost of 25% of the unit cost.

Test Points

The proposed test points are shown in Table A-1.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Main Engine

Page 3 of 5

Table A-1. Test Points

Measurement	No.	Flight Operations			Ground Checkout
		Control	Redline	Monitor	
MAIN ENGINE SUBSYSTEM					
Main Thrust Chamber Assembly (MC)					
Main Chamber Pressure	2	X	X	X	
LO_2 MC Valve PSN	1			X	X
Fuel MC Valve PSN	1			X	X
MC Igniter Circuit Monitor	1			X	X
MC LO_2 Flow	1	X		X	
Coolant Inlet Pressure	1			X	
MC LO_2 Injection Pressure	1			X	
MC LO_2 Igniter Valve PSN	1			X	X
Coolant Outlet Pressure	1			X	X
Coolant Inlet Temp	1		X	X	
Coolant Outlet Temp	1		X	X	
MC LO_2 Igniter Valve PSN	1			X	X
Preburner					
Preburner Chamber Pressure	2			X	X
PB Fuel Injection Pressure	1	X		X	X
PB LO_2 Injection Pressure	1			X	X
PB Fuel Injection Temp	1	X		X	
PB LO_2 Valve PSN	1	X		X	X
PB Igniter Circuit Monitor	1			X	X
PB LO_2 Flow	1	X	X		
PB Fuel Valve PSN	1			X	X
PB Fuel Flow	1	X	X		

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Main Engine

Table A-1. Test Points (continued)

	No.	Flight Operations			Ground Checkout
		Control	Redline	Monitor	
MAIN ENGINE SUBSYSTEM					
Fuel Turbopump Assembly (FTP)					
Fuel Pump Suction Pressure	2	X	X	X	X
Fuel Pump Discharge Pressure	1			X	X
Fuel Boost Pump Discharge Pressure	1	X			X
Fuel Turbine Inlet Pressure	1			X	X
Fuel Turbine Inlet Temp	1	X	X	X	
FTP Bearing Coolant in Pressure	1		X	X	X
Fuel Pump Suction Temp	1		X	X	
FTP Vibration	1		X	X	
FTP Speed	1		X	X	
Fuel Boost Pump Speed	1	X	X		
FTP Turbine Pressure Out	1			X	X
FTP Discharge Temp	1			X	
LO_2 Turbopump Assembly (LTP)					
LO_2 Pump Suction Pressure	2	X	X	X	X
LO_2 Pump MC Discharge Pressure	1			X	X
LO_2 Pump PB Discharge Pressure	1			X	X
LO_2 Turbine Inlet Pressure	1			X	X
LO_2 Turbine Inlet Temp	1	X	X	X	
LTP Bearing Coolant in Pressure	1		X		X
LO_2 Pump Suction Temp	1	X		X	
LTP Vibration	1		X	X	

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Main Engine

Table A-1. Test Points (continued)

	No.	Flight Operations			Ground
		Control	Redline	Monitor	Checkout
LTP Speed	1		X	X	
LO_2 Boost Pump Speed	1	X	X	X	
LTP Turbine Pressure Out	1			X	X
LO_2 Boost Pump Discharge Pressure	1	X			X
LO_2 Pump PB Discharge Temp	1			X	
PROPELLANT FEED SUBSYS SUBSYSTEM					
Main Fuel Valve PSN	1		X	X	X
Main LO_2 Valve PSN	1		X	X	X
Fuel Tank Outlet Pressure	1			X	X
LO_2 Tank Outlet Pressure	1			X	X
PROPELLANT TANK PRESSU-RIZATION CONTROLS					
Fuel Tank Pressurant Temp	1			X	
LO_2 Tank Pressurant Temp	1			X	
Fuel Pressurant Pressure	1			X	X
LO_2 Pressurant Pressure	1			X	X
LO_2 Pump Seal Cavity Purge Pressure	1		X	X	X
THRUST VECTOR CONTROL SUBSYSTEM					
Yaw Actuator PSN	1	X		X	X
Pitch Actuator PSN	1	X		X	X
Yaw Actuator Servo PSN	2			X	X
Pitch Actuator Servo PSN	2			X	X
Yaw Actuator Pressure In	1			X	X
Pitch Actuator Pressure In	1			X	X
Hydraulic Pump Out Pressure	2			X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Propellant Tank Pressurization Controls

Page 1 of 1

Function - Provides makeup pressurant for the fuel and oxidizer tanks during main engine operation, including pressure relief, and pressure regulation.

Characteristics

Total Units	-	2 (1 for each propellant)
Unit Weight	-	11.3 kg (25 lbs)
Unit Cost	-	$10,000
Maturity	-	Advanced technology

Failure Modes and Effects

Wearout

Pressurization valves are most susceptible to wear and result in the pressurant leakage.

Failure Rate

Wearout

Refurbished every 20 missions.

Average Refurbishment Costs

The main propulsion system is refurbished after 20 missions at a cost of 25% of the unit price.

Test Points

See Table A-1.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Hydraulic Thrust Vector Control

Function - Provides thrust vector control for yaw and pitch maneuvers during main engine operation.

Characteristics

Total Units	-	1 (partially redundant)
Unit Weight	-	19.5 kg (43 lbs)
Unit Cost	-	$60,000
Maturity	-	State-of-the-Art

Failure Modes and Effects

Random

1. System blockage is the most likely failure to be encountered in the hydraulic system. When it occurs, the problem results in loss of vehicle control. Its occurrence is limited by redundant design.

2. Fabrication or design deficiencies are the next most likely cause of failure. Leakage and bracket failures are the types of failures usually encountered. Generally non-catastrophic.

Wearout

1. Servo valve failure is the most likely wearout failure. Design should include two or more servo valves to preclude the normal catastrophic effects of this problem.

2. Seal leakage in hydraulic pump and actuator systems is the next most likely wearout failure. Its effects on flight are nil, but it requires subsequent replacement of the seals.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Hydraulic Thrust Vector Control

Page 2 of 2

Failure Rate

Wearout

System is refurbished after 20 missions.

Average Refurbishment Cost

The complete system is refurbished after 20 missions at a cost of 25% of the unit cost.

Test Points

See Table A-1.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Main Propulsion System

SUBSYSTEM: Propellant Feed

Page 1 of 1

Function - The propellant feed system provides propellant feed to the main engine, propellant line conditioning, and propellant fill, drain and dump.

Characteristics

Maturity - Advanced State-of-the-Art

Failure Modes and Effects

Random

The most likely failure is in the valves and controls for the propellant line conditioning which could result in excess propellant loss or slow engine start transient.

Wearout

The main engine prevalves may be subject to wearout and resultant propellant leakage.

Failure Rates

Wearout

Refurbished every 20 missions.

Average Unit Refurbishment Costs

The complete system is refurbished after 20 missions at a cost of 25% of the unit cost.

Test Points

See Table A-1.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Thruster Module

Function - To provide reaction control forces for attitude control and stationkeeping.

Characteristics

5 thrusters per module

4 modules per vehicle

Module Weight	-	31.7 kg (70 lbs)
Module Size	-	0.5 m x 1.3 m x 1.3 m (20" x 52" x 50")
Unit Cost/Module	-	$400,000
Maturity	-	Advanced Technology

Failure Modes and Effects

Random

1. Propellant valve leakage is the most probable failure mode. The effects are propellant loss, reaction force bias, and possible ignition overpressures due to propellant accumulation in the thrust chamber.
2. Igniter failure results in the loss of control force.
3. Propellant valve failure to open is a mode that can be either electrical or mechanical and results in loss of control force.

Wearout

1. The igniter has probably the highest wearout rate, assuming a spark igniter is used.
2. The propellant valves, which contain the only moving parts in the cluster, are subject to wearout.

Failure Rates

Wearout

The system is refurbished after 20 missions

Average Refurbishment Cost

The system is refurbished after 20 missions at a cost of 33% of the unit cost.

Test Points

A list of proposed test points is shown in Table A-2.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Thruster Module

Page 3 of 9

Table A-2. Test Points

Parameter	Number of Measurements	Monitored During Flight	Monitored on Ground
Pressures			
Thruster Modules	20	X	
Chamber	20	X	
Propellant Conditioning Modules			
Gas Generator Chamber	4	X	X
Hydrogen Pump Outlet	2	X	X
Oxygen Pump Outlet	2	X	X
Hydrogen Pump Inlet	2	X	
Oxygen Pump Inlet	2	X	
Hydrogen Turbine Outlet	2	X	
Oxygen Turbine Outlet	2	X	
Accumulator Modules			
Hydrogen Accumulator	1	X	X
Oxygen Accumulator	1	X	X
Controls Modules			
Hydrogen Line	1	X	X
Oxygen Line	1	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Thruster Module

Table A-2. Test Points (continued)

	Number Measurements	Monitored During Flight	Monitored on Ground
Temperatures			
Thruster Modules			
Hydrogen Valve	20	X	
Oxygen Valve	20	X	
Propellant Conditioning Modules			
Hydrogen Pump Inlet	2	X	
Oxygen Pump Inlet	2	X	
Hydrogen Bleed	1	X	
Oxygen Bleed	1	X	
Hydrogen Pump Outlet	2	X	
Oxygen Pump Outlet	2	X	
Hydrogen Turbine Inlet	2	X	
Oxygen Turbine Inlet	2	X	
Hydrogen Turbine Outlet	2	X	
Oxygen Turbine Outlet	2	X	
Gas Generator Gas	4	X	
Hot Side Oxygen Heat Exchanger Inlet	2	X	
Hot Side Oxygen Heat Exchanger Outlet	2	X	

Table A-2. Test Points (continued)

Parameter	Number of Measurements	Monitored During Flight	Monitored on Ground
Hot Side Hydrogen Heat Exchanger Inlet	2	X	
Hot Side Hydrogen Heat Exchanger Outlet	2	X	
Cold Side Oxygen Heat Exchanger Inlet	2	X	
Cold Side Oxygen Heat Exchanger Outlet	2	X	
Cold Side Hydrogen Heat Exchanger Inlet	2	X	
Cold Side Hydrogen Heat Exchanger Outlet	2	X	
Accumulator Modules			
Hydrogen Accumulator	1	X	
Oxygen Accumulator	1	X	
Control Modules			
None			
Events			
Thruster Modules			
On-off Commands	20	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Thruster Module

Table A-2. Test Points (continued)

Parameter	Number of Measurements	Monitored During Flight	Monitored on Ground
Propellant Conditioning Modules			
Hydrogen Gas Generator On-off	2	X	X
Oxygen Gas Generator On-off	2	X	X
Accumulator Modules			
None			
Control Modules			
Hydrogen Accumulator Pressure Switch	1	X	X
Oxygen Accumulator Pressure Switch	1	X	X
Hydrogen Line Pressure Switch	1	X	X
Oxygen Line Pressure Switch	1	X	X
Main Tank Pressurization On-off	2	X	X
Electrical			
Thruster Modules			
Hydrogen Valve Current	20		X
Oxygen Valve Current	20		X
Igniter Current	20	X	X

Table A-2. Test Points (continued)

Parameters	Number of Measurements	Monitored During Flight	Monitored on Ground
Propellant Conditioning Modules			
Hydrogen GG Valve Current	20		X
Oxygen GG Valve Current	20		X
GG Igniter Current	20	X	X
Accumulator Modules			
None			
Controls Modules			
None			
Miscellaneous			
Thruster Modules			
None			
Propellant Conditioning Modules			
Hydrogen Turbine Speed	2	X	X
Oxygen Turbine Speed	2	X	X
Accumulator Modules			
None			

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Thruster Module

Table A-2. Test Points (continued)

Parameters	Measurements	Monitored During Flight	Monitored on Ground
Controls Modules			
None			
Derived Data From Computer			
Thruster Modules			
Characteristic Velocity - C*	20	X	
Thrust	20	X	
Mixture Ratio	20	X	
Oxygen Flow Rate	20	X	
Hydrogen Flow Rate	20	X	
Specific Impulse	20	X	
Cumulative No. of Thruster Firings	20	X	
Cumulative Thruster Firing Duration	20	X	
Propellant Conditioning Modules			
G.G. Characteristic Velocity - C*	4	X	
G.G. Mixture Ratio	4	X	
G.G. Oxygen Flow Rate	4	X	
G.G. Hydrogen Flow Rate	4	X	
G.G. Number of Firings	4	X	

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Thruster Module

Table A-2. Test Points (continued)

Parameters	Number of Measurements	Monitored During Flight	Monitored on Ground
G.G. Cumulative Firing Duration	4	X	
Cumulative Turbine Operating Time	4	X	
Hydrogen Pump Horsepower	2	X	
Oxygen Pump Horsepower	2	X	
Hydrogen Heat Exchanger Efficiency	2	X	
Oxygen Heat Exchanger Efficiency	2	X	
<u>Accumulator Modules</u>			
None			
<u>Controls Modules</u>			
None			

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Propellant Conditioner Module

Page 1 of 2

Function - To pump liquid propellant from the main tank to the propellant storage unit and to change the propellant from a liquid to a gas at a controlled temperature and pressure.

Characteristics

Description

The module will consist of a turbopump, a heat exchanger, and a gas generator with associated controls and instrumentation. Two modules will function in parallel for redundancy.

Total Modules	-	4 (2 for each propellant)
Weight/Module	-	18 kg (40 lbs)
Volume/Module	-	0.057 m^3 (2 ft^3)
Cost/Module	-	$120,000
Maturity	-	The technology is only in the experimental stage. Miniaturization problems can be anticipated due to the low flow rates required.

Failure Modes and Effects

Random

1. A hot gas valve is anticipated to have the highest random failure rate. The hot gas valve will modulate the flow rate between the heat exchanger and the turbine and provide turbine speed control. Malfunction will cause shutdown of the propellant conditioning module because of turbine overspeed or underspeed. The redundant propellant conditioning unit will continue to provide conditioned propellant.

2. Gas generator valve leakage is a highly probably failure mode. The effects are propellant loss, possible ignition overpressure, and possible ice formation. Gas generator controls must provide overboard venting of the gas generator between restarts to prevent propellant accumulation and possible detonation on restart.

3. Leakage of any of the other valves in the system is also highly likely. The effects of such leakage will depend on the details of the design of the control system.

Wearout

1. The turbopump, being the major mechanical component, is the most likely to wear out. Wearout may consist of bearing wear providing increased friction and reduced efficiency with ultimate loss of pumping capability.

2. The igniter is probably subject to wearout, although there are few ignitions of the gas generators compared to the thrusters.

Failure Rates

Wearout

The system is refurbished after 20 missions.

Average Refurbishment Cost

The system is refurbished after 20 missions at a cost of 33% of the unit cost.

Test Points

See Table A-2.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Accumulator

Function - Provides storage for pressure and temperature conditioned gaseous propellant.

Characteristics

Total Units	-	2 (1 for each propellant)
Weight/Unit	-	13.6 to 22.7 kg (30 to 50 lbs)
Size	-	0.46 to 0.61 m (1.5 to 2.0 ft) diameter sphere
Unit Cost	-	$20,000
Maturity	-	Current State-of-the-Art

Failure Modes and Effects

Random

1. Contamination may require removal and cleaning.
2. Structural failure from external damage or overpressurization could be catastrophic.

Wearout

None

Failure Rates

No failures during vehicle life.

Average Refurbishment Costs

100% of unit cost if required.

Test Points

See Table A-2.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Auxiliary Propulsion System

SUBSYSTEM: Controls Unit

Function - The propellant storage controls unit provides propellant at controlled temperature and pressure, to the propellant accumulators and to the thrusters.

Characteristics

Total Units	-	2 (1 for each propellant)
Weight/Unit	-	9.1 kg (20 lbs)
Size	-	0.028 m^3 (1 ft^3)
Unit Cost	-	\$120,000
Maturity	-	Advanced technology

Failure Modes and Effects

Random

1. Failure of a pressure switch in the pressure regulation system downstream of the accumulator is most likely and would probably simply result in the regulated propellant pressure exceeding specified tolerance during checkout.

2. Failure of a pressure switch in the accumulator pressure control system is probably equally likely. This could possibly cause loss of propellant through the accumulator relief valves due to overpressurization.

3. Leakage of a solenoid valve in the "bang-bang" pressure regulation system is a relatively high possibility. This would result in overpressurization downstream of the accumulators. This would result in high thrust, off-mixture ratio operation of the thrusters.

Wearout

1. The solenoid valves in the pressure regulation system could wear out depending upon duty cycle and pressure tolerance. The wear would affect leakage and response.

2. The pressure switches could exhibit wearout characteristics due to cycling of the sensing element.

Failure Rates

Wearout

The system is refurbished after 20 missions.

Average Refurbishment Cost

The system is refurbished after 20 missions at a cost of 33% of the unit cost.

Test Points

See Table A-2.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Electrical Power

Function - Provides nominal 28 V dc power for the Tug subsystems.

Characteristics

Description

System consists of two fuel cell power plants and associated distribution and control elements.

Average Power	-	300 watts
Weight	-	77 kg (170 lbs)
Cost/Fuel Cell	-	$535,000
Maturity	-	Data is based on a fuel cell technology program conducted by NASA.

Failure Modes and Effects

Random

1. Coolant pump failure.
2. Pressure regulator failure
3. Control sensor failure.

Wearout

1. Carbonate buildup on electrodes.
2. Coolant pump failure.

Failure Rate

Random

MTBF/cell = 33,000 hours.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Electrical Power

Wearout

System is refurbished after 2000 hours of operation.

Average Refurbishment Cost

The system is refurbished after 2000 hours of operation at a cost of 25% of the unit cost.

Test Points

Measurement	No.	In-Flight	Ground Checkout
Temperature	1	X	X
Fuel Cell Stack			
Voltage	3	X	X
Current	3	X	X
Main Power Distribution			
Voltage	1	X	X
Current	1	X	X

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Avionics

SUBSYSTEM: Guidance Navigation and Control

Function - Provide the guidance, navigation and control function for the Tug.

Characteristics

Unit	No. of Units	Total Weight kg (lbs)	Total Power (Watts)	MTBF Unit (hr)	Cost ($)
Micron IMU	3	10.9 (24)	60	5,000	124,000
Horizon Sensor	1	9.1 (20)	20	30,000	222,000
Star Tracker	2	5.4 (12)	5	250,000	178,000
Control Electronics	1	4.5 (10)	5	5,000	27,000

Maturity - The equipment selected is of mature status with the exception of the MICRON IMU. This component is being developed under an Air Force contract for the Air Force Avionics Laboratory and is expected to be available consistent with Tug planning.

Failure Modes

Semi-conductor failures.

Average Refurbishment Cost

A failed unit is repaired at a cost equal to 15% of the unit cost on the average.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Avionics

SUBSYSTEM: Rendezvous and Docking

Function - This subsystem supplies the Scanning Laser Radar for rendezvous and docking.

Characteristics

Number of Units	- 2
Weight/Unit	- 13.6 kg (30 lb)
Power	- 20 watts
Cost/Unit	- $445,000
Maturity	- Specific design required for Tug would be an extension of current technology programs.

Failure Modes

Semi-conductor failures in:

1. The laser transmitter
2. The beam steerer
3. Processing electronics

Failure Rate

MTBF - 3,000 hours

Average Refurbishment Cost

A failed unit is repaired at a cost equal to 15% of the unit cost on the average.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Avionics
SUBSYSTEM: Data Management
Page 1 of 1

Function - Provides the data management function for the Tug.

Characteristics

Unit	No. of Units	Total Weight kg (lb)	Total Power (Watts)	MTBF (Unit) (hr)	Cost ($)
Computer	3	9.1 (20)	36	10,000	89,000
Voter	1	4.5 (10)	5	30,000	107,000
Mass Memory	2	11.3 (25)	20	5,000	89,000
Bus Control Unit	1	4.5 (10)	20	30,000	142,000
Data Bus Adapter	10	6.8 (15)	100	8,500	53,000

Maturity - The technology for the data management subsystem is mature, but the specific system components and the required redundancy management; checkout, et al, programs require design and development.

Failure Modes

1. Memory unit failure
2. I/O semi-conductor failure
3. CPU semi-conductor failure

Average Refurbishment Cost

A failed unit is repaired at a cost equal to 15% of the unit cost on the average.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Avionics
SUBSYSTEM: Communication
Page 1 of 2

Function - Supply communication for the Tug.

Characteristics

Item	No. of Units	Total Weight kg, (lb)	Total Power (Watts)	MTBF (Unit) (hr)	Cost ($)
S-Band Antennas	2	0.9 (2)	-	-	-
S-Band Cables	-	2.3 (5)	-	-	-
S-Band Hybrids & Dividers	3	1.4 (3)	-	-	-
S-Band Diplexers	1	0.9 (2)	-	-	-
Ferrite Switches	2	0.9 (2)	2	150,000	5,000
Receiver/Demodulator	2	5.9 (13)	9	50,000	71,000
Baseband Assembly	2	2.3 (5)	2	50,000	35,000
Transmitter	2	6.8 (15)	30	50,000	71,000
Power Amplifier	2	4.5 (10)	70	20,000	35,000

Maturity - The selected equipment is currently available in heavier weight design. Advantage of advanced technology has been assumed in the specifications above.

SUMMARY REFURBISHMENT DATA SHEET

SYSTEM: Avionics
SUBSYSTEM: Communication

Failure Modes

Semi-conductor failures on:

1. The power amplifier
2. The transmitter
3. The receiver/demodulator

Average Refurbishment Cost

A failed unit is repaired at a cost equal to 15% of the unit cost on the average.

B. REFURBISHMENT OPERATION SHEETS

The "operations sheets" describe the operations involved in maintaining and refurbishing each of the major vehicle areas. These sheets describe the tasks to be performed during the three levels of maintenance: (1) routine maintenance which is performed after each mission and usually consists of a visual inspection, minor calibration, leak checks, etc.; (2) engineering inspection which is performed less frequently and usually consists of disassembling the system into its major components and a more detailed inspection than that performed during the routine inspection; and (3) replace or refurbish maintenance level which usually consists of removing the system from the vehicle and replacing it with a new or refurbished system. The frequency at which the various levels of maintenance are performed, the hardware replaced and the manpower required to perform each maintenance level are also described.

The manhours required to perform each level of maintenance was established by first determining the tasks required and then estimating the manhours required to perform each task. From a knowledge of the system and the tasks involved, a maintenance crew was established, i.e., number of technicians, inspectors, engineers, etc. The elapsed time to perform the maintenance level was determined by dividing the estimated manhours by the number of actual workers, viz., number of technicians in the maintenance crew. The total manhours required to perform the maintenance level was then obtained by multiplying the elapsed time by the total crew.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Basic Structure

Page 1 of 2

Crew

Engineer - 1
Technician - 2
3 Total

Routine Inspection

1. Operations - Visual inspection of basic structure for apparent structural damage after every mission.
2. Equipment - None.
3. Manpower requirements - This function will require 2 technicians for 1 shift.

   Total manhours - 8 hours x 3 men = 24 manhours.

Engineering Inspection

1. Operations - More detailed inspection. All attachment points, e.g., around propellant tanks, etc., are visually inspected. This inspection is performed whenever the thermal insulation is removed from the propellant tanks.
2. Equipment - None.
3. Manpower requirements - This task will require 2 technicians for 2 shifts.

   Total manhours - 16 hours x 3 men = 48 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Basic Structure

Replace/Refurbish

1. Operations - Same as engineering inspection except include X-ray and ultrasonic testing every 10th mission.

2. Equipment - X-ray and ultrasonic equipment.

3. Manpower requirements - 2 technicians for 3 shifts.

   Total manhours - 24 hours x 3 men = 72 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Meteoroid Shield
Page 1 of 1

Crew

Engineer - 1
Technicians - 2
3 Total

Routine Inspection

1. Operations - Remove shield from vehicle and visually inspect for structural damage (removal of the shield from the vehicle is required to inspect the tank insulation system). Replace shield. This is done after every flight.

2. Equipment - Special tools for removing and handling shield.

3. Manpower requirements -

   Remove and replace shield - 2 technicians for 16 hours

   Visual inspection - 2 technicians for 4 hours

   Total manhours - 20 hours x 3 men = 60 hours.

Engineering Inspection

None

Replace/Refurbish

1. Operations - Same as routine inspection except the old shield is replaced with a new shield.

2. Equipment - Same as for routine inspection.

3. Manpower requirements - 60 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Tug/Payload Docking Mechanism

Page 1 of 1

Crew

Engineer - 1
Technician - 2
3 Total

Routine Inspection

1. Operations - Visual inspection for apparent structural damage. Perform functional checks of latches and shock absorbers. Perform He and hydraulic pressure checks. This is done after every mission.
2. Equipment - Pressure check equipment.
3. Manpower requirements - 2 technicians for 1 shift.

   Total manhours - 8 hours x 3 men = 24 manhours.

Engineering Inspection

None

Replace/Refurbish

1. Operations - Remove docking mechanism and replace with a refurbished system. Perform a routine inspection. This is done every 10th mission.
2. Equipment - Sling and hoist for removing docking system.
3. Manpower requirements -

   Remove and replace - 2 technicians for 1 shift
   Routine inspection - 2 technicians for 1 shift
   Total manhours - 16 hours x 3 men = 48 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Tug/Shuttle Docking Mechanism

Crew

Engineers - 1
Technicians - 2
3 Total

Routine Inspection

1. Operations - Visual inspection for apparent structural damage. Perform functional checks of latches and shock absorbers. Performed after every mission.
2. Equipment - None
3. Manpower requirements - 2 technicians for 1 shift.

   Total manhours - 8 hours x 3 men = 24 manhours.

Engineering Inspection

None

Replace/Refurbish

1. Operations - Remove docking mechanism and replace with refurbished system. Perform a routine inspection. This is done every 10th mission.
2. Equipment - Sling and hoist for removing docking system.
3. Manpower requirements -

   Remove and replace - 2 technicians for 1 shift

   Routine inspection - 2 technicians for 1 shift

   Total manhours - 16 hours x 3 men = 48 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Propellant Tanks

Crew

Engineers - 1
Technicians - 3
4 Total

Routine Inspection

1. Operations - Perform a visual inspection and a leak test with helium after every mission.
2. Equipment - Pressurant gas supply and helium leak detectors.
3. Manpower requirements - 3 technicians for 4 shifts.

   Total manhours - 32 hours x 4 men = 128 manhours.

Engineering Inspection

None

Replace/Refurbish

Every 20th mission the propellant tanks are removed and replaced due to design life limitations. It has been estimated that 1100 manhours will be required to accomplish this task. Table A-3 lists the operations to be performed and Table A-4 presents a manpower estimate.

Table A-3. Propellant Tanks Replacement Sequences

1. Install Tug less engine, meteoroid shields and insulation vertically in support fixture, using aft Tug/Shuttle attach points.
2. Disconnect (at forward end only) lines, cabling leading from forward equipment bay to aft section. Secure away from tank to avoid damage or interference with tank remover procedure.
3. Use hoist to position and attach hoist ring to payload support points.
4. Disconnect forward shell from LH_2 tank.
5. Lift forward shell clear of LH_2 tank dome, translate and lower to support fixture. Leave hoist ring installed. (Refurbishment of forward bay components is then performed in parallel with tank replacement operations.)
6. Use hoist to position and attach LH_2 tank hoist ring to LH_2 tank at primary (flight) structural attach points (5 places).
7. Disconnect LH_2 tank aft structural attachments, plumbing and wiring connections.
8. Hoist LH_2 tank clear of aft truss and external lines and lower to transporter. Remove hoist ring.
9. (Remove any installations in center bay which would interfere with LO_2 tank removal.)
10. Use hoist to position and attach hoist ring to LO_2 tank at periferal tabs on primary tank structural attach ring.
11. Disconnect LO_2 tank structural attachments, plumbing and wiring.

Table A-3. Propellant Tanks Replacement Sequences (continued)

12. Hoist LO_2 tank clear of truss and external lines and lower to tank transporter. Remove hoist ring.

13. X-ray (or other) primary tank structural attachments, critical truss structure joints, etc., and repair or replace as necessary. (Note: Primary structural replacements will require supplemental equipment and fixtures to preserve and/or restore and re-certify the alignment.)

14-20. (Reverse of tasks 6 through 12. Apply factor of 1.25 to account for longer times involved in reconnections and detail tests and inspections. Duration raised to next whole number for simplicity.)

21. Connect lines and purge both tanks and all associated plumbing with GN_2.

22. Pressurize both tanks to flight pressures with GN_2 with Krypton tracer. Conduct gross pressure decay check.

23. Conduct general survey of tank surfaces and detailed survey of all plumbing connections for evidence of leakage. Correct as possible and verify leakage integrity.

24-27. (Reverse of Tasks 2 through 5. Apply 1.25 factor to times.)

28. Conduct aft equipment bay refurbishments.

29. Remove Tug from bay and transfer to normal maintenance bay (for engine installation, all systems check and meteoroid panels and insulation reinstallations.)

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Propellant Tanks

Table A-4. Tug Propellant Tank Replacement Task Assessment

Task	Crew	Duration	M. H. (1)
1	8	3	24
2	5	2	10
3	5	1	5
4	6	2	12
5	6	1	6
6	6	1	6
7	10	3	30
8	8	1	8
9	6	2	12
10	8	2	12
11	10	3	30
12	8	1	8
13	10	48	480
14	8	2	16
15	10	4	40
16	8	3	24
17	6	3	18
18	8	2	16
19	10	4	40
20	6	2	12
21	4	2	8
22	4	1	4
23	4	4	16
24	6	2	12
25	6	3	18
26	5	2	10
27	5	3	15
28	(Not Part of Tank Replacement)		
29	8	3	24

Crew Composition	
As appropriate	
Leadman	- 1
Q.C. (Elect.)	- 1
Q.C. (Mech.)	- 1
Mechanic (Struct.)	- 3
Mechanic (Mech. & Plumbing	- 2
Mechanic (Elect. & Electr.)	- 2
Total	10

Total Duration - 110 Hours
Total M.H. - 1100 Hours (Total Crew Continuously Assigned for Duration of Replacement.)

(1) Applies only to specific task. Remainder of crew is occupied with preps for other tasks.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Interface Panels

Crew

Engineers - 1

Technicians - 2

3 Total

Routine Inspection

1. Operations - Inspect for apparent structural damage and physical alignment. Check all valve positions and voltages.
2. Equipment - Voltmeter.
3. Manpower requirements - 2 technicians for 4 hours.

   Total manhours - 4 hours x 3 men = 12 manhours.

Engineering Inspection

1. Operations - Replace connectors, seals, O-rings, etc. Perform a routine inspection. This is performed after the 5th and 15th missions in IOC flight phase.
2. Equipment - Voltmeters, seal removers, etc.
3. Manpower requirements -

   Connector and seal replacement - 2 technicians for 1 shift

   Routine inspection - 2 technicians for 4 hours

   Total manhours - 12 hours x 3 men = 36 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Interface Panels

Replace/Refurbish

1. Operations - Remove and replace with new panels. Perform a routine inspection. This is performed every 10th mission.

2. Equipment - Special tools for panel removal.

3. Manpower requirements -

   Remove and replace - 2 technicians for 1 shift

   Routine inspection - 2 technicians for 4 hours

   Total manhours - 12 hours x 3 men = 36 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Propellant Tank Insulation System

Crew

Engineers	-	1
Inspectors	-	0.5
Technicians	-	4
		5.5 Total

Routine Inspection

1. Operations - Review flight data. Remove the meteoroid shield and perform a visual inspection of the insulation system. Perform special test to determine adequacy of insulation blankets (actual test is undefined). Replace the meteoroid shield. This maintenance level is performed after every mission.
2. Equipment - TBD (dependent on special test requirements).
3. Manpower requirements -

   Remove and replace meteoroid shield (this time is accounted for under meteoroid shield maintenance.)

Inspect and check purge bay	-	16 manhours
Inspect and check insulation	-	20 manhours
Inspect and check vent valves	-	10 manhours
		46 manhours

   $$\text{Elapsed Time} = \frac{46 \text{ manhours}}{4 \text{ technicians}} = 11.5 \text{ Hours}$$

   Total manhours - 5.5 men x 11.5 hours = 64 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Propellant Tank Insulation System

Engineering Inspection

1. Operations - Review the flight data. Remove the meteoroid shield. Remove the insulation and replace with reconditioned insulation. Perform a vacuum test to check the installation. Replace meteoroid shield.

2. Equipment - Vacuum chamber having a capability of at least 10^{-3} Torr. No cold wall or heat lamp capability is required.

3. Manpower requirements -

Remove and replace meteoroid shield (this time is accounted for under meteoroid shield maintenance).

Inspect and check purge bag	16 manhours
Inspect and check insulation	20 manhours
Remove insulation for reconditioning	150 manhours
Install reconditioned insulation	300 manhours
Inspect and check vent valves	10 manhours
	496 manhours

$$\text{Elapsed Time} = \frac{496 \text{ manhours}}{4 \text{ technicians}} = 124 \text{ hours}$$

Total manhours - 5.5 men x 124 hours = 682 manhours.

In addition to the cost of the above manpower requirements, a cost of $15,000 has been estimated for the vacuum chamber test. This is based on an 8-shift operation consisting of the following:

Vehicle set-up in the chamber	-	2 shifts
Vacuum test	-	1 shift
Repair insulation	-	2 shifts
Vacuum test	-	1 shift
Tear down	-	2 shifts
		8 shift total

During the actual running of the test, a cost of $50/hour for consumables was assumed. For the total 8-shift operation a cost of $50/hour for the chamber crew was assumed. Also, for the total 8-shift operation, a vehicle crew consisting of 10 men at a cost of $17/hour/man was assumed.

Replace/Refurbish

1. Operations - Review the flight data. Remove the meteoroid shield. Remove the insulation and replace with a new system. Perform a vacuum chamber test to check the installation. Replace the meteoroid shield.
2. Equipment - Vacuum chamber.
3. Manpower requirements -

   Remove and replace meteoroid shield (this time is accounted for under meteoroid shield maintenance).

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Propellant Tank Insulation System

Remove and replace purge bay	- 48 manhours
Check insulation	- 20 manhours
Remove and replace insulation	- 450 manhours
Remove and replace vent valves	- 20 manhours
Check purge bay	- 16 manhours
Check vent valves	- 10 manhours
	564 manhours

$$\text{Elapsed time} = \frac{564 \text{ manhours}}{4 \text{ technicians}} = 141 \text{ hours}$$

Total manhours = 55 men (total crew) x 141 hours = 776 manhours.

The cost of the vacuum chamber test has been estimated to be $15,000.

SUMMARY REFURBISHMENT OPERATIONS SHEETS

SYSTEM: Main Propulsion

Crew

Engineers	-	1
Inspectors	-	1
Technicians	-	6
Analysts	-	1
		9 Total

Routine Inspection

1. Operations - Review flight data, perform various functional tests, pressure tests, structural integrity tests, alignment checks and calibration tests. This is done after every flight.
2. Equipment - He purge system, pressure gage, leak detection, X-ray, bench flow calibrating equipment.
3. Manpower requirements -

Engine purge	2	manhours
Remove and replace instrumentation sensors	8	"
Visual inspection	16	"
Mechanical inspection	12	"
Leak check	16	"
Functional check	28	"
Structural integrity	10	"
Electrical continuity	4	"

Functional trend analysis	16 manhours
Instrumentation calibration	36 manhours
	148 manhours

$$\text{Elapsed time} = \frac{148 \text{ manhours}}{7 \text{ technicians and analysts}} = 21 \text{ hours}$$

Total manhours - 9 men x 21 hours = 189 manhours.

Engineering Inspection

1. Operations - Review the flight data, remove the main engine for shipment to manufacturer for a teardown inspection. Perform the tests as for a routine inspection. This is done for the mature vehicle every 10th flight.

2. Equipment - Same as for routine inspection plus an engine dolly.

3. Manpower requirements -

Engine purge	2	manhours
Remove and replace engine	160	"
Package and ship	40	"
Visual inspection	16	"
Mechanical inspection	12	"
Leak check	16	"
Functional check	28	"
Structural integrity	10	"
Electrical continuity	4	"
Functional trend analysis	16	"
Instrument calibration	36	"
	340	manhours

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Main Propulsion

Page 3 of 4

$$\text{Elapsed time} = \frac{340 \text{ manhours}}{7 \text{ technicians and analysts}} = 49 \text{ hours}$$

Total manhours - 9 men x 49 hours = 441 manhours.

Replace/Refurbish

1. Operations - Same as engineering inspection except the hydraulic components, control system valves and propellant ducting are also removed. This maintenance level is performed after every 20th flight for the mature vehicle.

2. Equipment - Same as engineering inspection.

3. Manpower requirements -

Engine purge	2	manhours
Remove and replace:		
Main engine	160	"
Hydraulic components	40	"
Control system valves	80	"
Propellant ducting	20	"
Package and ship	40	"
Visual inspection	16	"
Mechanical inspection	12	"
Leak check	16	"
Functional check	28	"
Structural integrity	10	"
Electrical continuity	4	"
Functional trend analysis	16	"
Instrument calibration	36	"
	480	manhours

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Main Propulsion

$$\text{Elapsed time} = \frac{\text{480 manhours}}{\text{7 technicians and analysts}} = \text{69 hours}$$

Total manhours - 9 men x 69 hours = 621 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Auxiliary Propulsion System

Page 1 of 3

Crew

Engineers	-	2
Inspectors	-	2
Technicians	-	8
Analysts	-	3
		15

Routine Inspection

1. Operations - Review flight data, perform leak test, proof pressure, functionals, calibration, etc. This is done after every flight.

2. Equipment - Automated checkout equipment for vehicle level functionals. Equipment must provide gas pressurization of the APS, electrical functionals, leak tests, monitor the system test results and provide go/no-go type indications.

3. Manpower requirements - 2 shifts required
   Total manhours - 16 hours x 15 men = 240 manhours.

Engineering Inspection

1. Operations - Review the flight data. Remove thruster modules, propellant conditioner modules and propellant control units from the vehicle. Disassemble modules to the major subassembly level. Replace thruster igniters, propellant filters, intercomponent seals, etc. Complete bench tests, functionals and calibration of all modules. Repeat vehicle level routine inspection after installation on the vehicle. This maintenance level is performed after every tenth flight for a mature vehicle.

2. Equipment - Bench test equipment to provide functionals and gas flow calibrations. A liquid nitrogen flow bench may be required for turbopump flow check.

3. Manpower requirements -

Thruster Modules	
Remove and replace	32 manhours
Bench test	128 manhours
Propellant Conditioner	
Remove and replace	96 manhours
Bench test	128 manhours
Control unit	
Remove and replace	16 manhours
Bench test	64 manhours
	464 manhours

$$\text{Elapsed time} = \frac{464 \text{ manhours}}{8 \text{ technicians}} = 58 \text{ hours.}$$

Total manhours - 58 hours x 15 men =	870 manhours
+ Routine Inspection	240 manhours
	1,110 manhours

Replace/Refurbish

1. Operations - Review the flight data. Remove the auxiliary propulsion system from the vehicle and replace with a refurbished system. Perform a routine inspection. This is done after the 20th flight.

2. Equipment - Same as for routine inspection.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Auxiliary Propulsion System

Page 2 of 3

3. Manpower requirements -

Thruster	
Remove and replace	32 manhours
Propellant Conditioner	
Remove and replace	96 manhours
Control unit	16 manhours
	144 manhours

$$\text{Elapsed time} = \frac{144 \text{ manhours}}{8 \text{ technicians}} = 18 \text{ hours}$$

Total manhours - 18 hours x 15 men =	270 manhours
+ Routine Inspection	240 manhours
	510 manhours

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Electrical Power System

Crew

Engineers	-	1.0
Inspectors	-	0.5
Technicians	-	2.0
		3.5

Routine Inspection

1. Operations - Review flight data, visual inspection of the electrodes for evidence of excessive carbonate buildup, and performance of an automated electrical test wherein voltage and current outputs are monitored under various load conditions. The electrical test would be commanded by the on-board computer and the test data would be telemetered to a data reduction center for analysis. This is performed after each mission.

2. Manpower requirements - 2 technicians for one shift
   Total manhours - 8 hours x 3.5 men = 28 manhours.

Engineering Inspection

1. Operations - At key milestones in the development program, the fuel cells would be removed and taken to a laboratory for a more extensive visual inspection and checkout on a unit level tester. Perform a routine inspection after installation.

2. Manpower Requirements

Remove and replace	32 manhours
Test	64 manhours
	96 manhours

SUMMARY REFURBISHMENT OPERATIONS SHEET

$$\text{Elapsed time} = \frac{96 \text{ manhours}}{2 \text{ technicians}} = 48 \text{ hours}$$

Total manhours - 48 hours x 3.5 men =	168	manhours
+ Routine inspection	28	manhours
	196	manhours

Replace/Refurbish

1. Operations - After 2000 hours of operation the system is removed and replaced with a refurbished system.

2. Manpower requirements

   Remove and replace 32 manhours

$$\text{Elapsed time} = \frac{32 \text{ manhours}}{2 \text{ technicians}} = 16 \text{ hours}$$

Total manhours - 16 hours x 3.5 men = 56 manhours.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Avionics

Crew

Engineers	-	2
Inspectors	-	2
Technicians	-	8
		12

Routine Inspection

1. Operations - This will be performed after each flight and will consist of reviewing the flight data, visual inspection of electrical cables and connectors, and running the on-board COFI routines which exercise BITE in the subsystems. In addition, the MICRON IMU will be removed every fifth flight for recalibration.

2. Manpower requirements

Guidance, Navigation and Control	32 manhours
Rendezvous and Docking	16 manhours
Data Management	32 manhours
Communication	32 manhours
	112 manhours

$$\text{Elapsed time} = \frac{112 \text{ manhours}}{8 \text{ technicians}} = 14 \text{ hours}$$

Total manhours - 14 hours x 12 men = 168 manhours.

Engineering Inspection

1. Operations - At key points in the flight program, the avionics system will be removed from the vehicle and each unit checked out on a unit level tester. The system will then be reinstalled on the vehicle and a routine inspection performed.

2. Manpower Required

Guidance, Navigation and Control	288 manhours
Rendezvous and Docking	48 manhours
Data Management	224 manhours
Communication	152 manhours
	712 manhours
	(includes routine inspection)

Elapsed time = $\frac{712 \text{ manhours}}{8 \text{ technicians}}$ = 89 hours

Total manhours - 89 hours x 12 men = 1,068 manhours.

Replace/Refurbish

1. Operations - The system is removed and replaced with a repaired system. A routine inspection is then performed.

SUMMARY REFURBISHMENT OPERATIONS SHEET

SYSTEM: Avionics

2. Manpower Requirements

Guidance, Navigation and Control	88 manhours
Rendezvous and Docking	32 manhours
Data Management	112 manhours
Communications	72 manhours
	304 manhours

Elapsed time $= \frac{304 \text{ manhours}}{8 \text{ technicians}} =$ 38 hours

Total manhours - 38 hours x 12 men = 456 manhours.

APPENDIX B. TOTAL TUG TURNAROUND COST COMPARISON

The objective of this study was to determine from a "bottoms-up" approach the average cost of maintaining the Tug vehicle. The costs generated in this study were only for Tug maintenance or refurbishment. Other Tug turnaround costs were not considered. Operations or functions that are usually considered in total Tug turnaround costs are listed below:

Launch Operations

Recovery Operations

Vehicle Maintenance

Propellants

Command and Control

Range and Base Support

Facility and Equipment Maintenance

Replacement Training

In-Plant Engineering Support

Program Integration and Management

The only function or operation that has been addressed in this study is "Vehicle Maintenance." A cost for each one of the above functions as determined from The Aerospace Corporation cost estimating relationships (CER's) is given in Table B-1. Also shown in the table is the cost for vehicle maintenance as determined from this study for a mature vehicle. Using the "bottoms-up" estimate for vehicle maintenance, the total direct turnaround cost per flight is \$400, 000 of which 68 percent is for vehicle maintenance. Based on the assumption of 12.9 flights per year, the total Tug turnaround cost per flight is \$1, 010, 000 of which approximately 27 percent is for vehicle maintenance.

Table B-1. Total Tug Turnaround Costs
Operations (10 Years, 129 Flights Total, 2 Sites)

	DETERMINED FROM COST ESTIMATING RELATIONSHIPS	DETERMINED FROM THIS STUDY
Direct		
Ground		
Launch Operations	$26 K/Flight	
Recovery Operations	$4 K/Flight	
Vehicle Maintenance	$477 K/Flight	$273 K/Flight
Propellants	$9 K/Flight	
Flight		
Command and Control	$88 K/Flight	
Indirect		
Range and Base Support	$950 K/Year	
Facility and Equipment Maintenance	$2,020 K/Year	
Replacement Training	$400 K/Year	
In-Plant Engineering Support	$2,250 K/Year	
Program Integration and Management	$2,250 K/Year	

APPENDIX C. DEDICATED TUG REFURBISHMENT CREW COST ESTIMATE

The manpower costs as derived in this study assume the existence of a labor pool from which the necessary manpower is obtained on an as-needed basis. Tug refurbishment then is charged only for the manhours actually expended refurbishing the Tug. The average manpower costs for the mature vehicle (OC) was determined to be $42,000 per flight.

The total Tug refurbishment crew size for all the major vehicle areas was 52 men. By assuming some multiple usage of personnel, this can be reduced to 37 men, 5 engineers and 32 technicians. The crew cost on a yearly basis at $17.00 per hour average is $1,258,000 per year. Assuming 10 flights per year, the manpower cost per mission is $125,800.

Table C-1 shows a comparison of the two manpower concepts. The hardware cost per mission is that derived in the study and is independent of the maintenance manpower concept.

Which maintenance manpower concept is more realistic is not clear. In the final analysis, it will be dependent on the maintenance philosophy established for the whole STS operation. If the launch rates are such that no conflict arises from common usage of people and the required skills are compatible, the maintenance manpower pool concept may be feasible. The cost per flight of a dedicated maintenance crew concept is strongly dependent on the launch rate. For low launch rates, e.g., 10 Tug flights per year, the maintenance crew could be utilized for other tasks, e.g., the launch crew. The crew could also perform maintenance on some of the equipment removed from the vehicle that is normally sent back to the manufacturer for repair. As the number of Tug flights per year approaches 30, the difference in the cost per mission for a labor pool and a dedicated crew diminishes. Hence, for costing purposes involving high Tug flights per year, the question of which manpower concept to use is immaterial.

Table C-1. Average Tug Refurbishment Cost Estimate
- Mature Vehicle -

MANPOWER CONCEPT	LABOR	HARDWARE	TOTAL
Labor Pool (1)	$42,000/Mission	$231,000/Mission	$273,000/Mission
Dedicated (2) Crew	$126,000/Mission	$231,000/Mission	$357,000/Mission

NOTE: (1) Labor costs based on existence of labor pool. Labor costs based on actual manhours spent refurbishing Tug.

(2) Labor costs based on existence of a dedicated maintenance crew of 37 men at a cost of $17.00 per hour average and a launch rate of 10 flights per year.

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